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The Deltic 3,300 h.p. diesel-electric locomotive

The Deltic Locomotive

By C. M. COCK, M.I.Mech.E., M.I.E.E., A.M.I.E.(Aust.), M.I.Loco.E., General Manager, Traction Department.

This article is in all essentials a reproduction of the Paper read by the author before the Institution of Electrical Engineers in London on 11th December 1958. The English Electric Company designed and built the Deltic locomotive as a private venture and offered it to British Railways for trials in 1955. After comprehensive tests of the prototype, and its successful operation in regular service, British Railways ordered twenty-two of these locomotives in 1958 as part of the modernisation programme.

INTRODUCTION

MANY RAILWAYS OF THE WORLD to-day are faced with the problem of improving their services, to compete with other modern forms of transport, to meet increased traffic due to national development or to reduce their working expenses. The trend is therefore to heavier trains and higher speeds, which require more powerful locomotives for operation on existing track or track improvements for more efficient locomotive operation. The ultimate restriction on the movement of trains on any railway system is the track.

The Track

To reduce the cost of the permanent way, many oversea railways have been built to poor standards, regardless of the effect on train performance. In hilly or undulating country the natural contours were followed to minimize banks, cuttings, bridges and tunnels, while the weight of the rail, the sleeper spacing and the ballast were barely sufficient. Some railways have been built with no ballast at all.

Poor permanent way imposes limits on axle load and speed, and restricts operation of the train services; cases can be quoted where luxury passenger trains with adequate modern motive power are unable to compete with road transport even over long distances because of the better schedule speeds of the latter. Although powerful locomotives can be built to run on poor permanent way, they often are of complicated and expensive design and are still subject to the speed restrictions imposed by the track. Improvements in the permanent way, while obtaining better conditions for the locomotive, involve heavy capital expenditure. Many railways, particularly those in financial difficulty, compromise with the more powerful locomotive as being in some measure the less costly way of improving the train services.

The Locomotive

In meeting the demand for more powerful locomotives, the designer faces considerable difficulty in keeping the locomotive weight within the limits imposed by the track. The characteristic performance of a diesel locomotive, shown in Fig. 1, is fixed by the engine power output. It normally is defined at the high-speed end by the track speed limit and at the other end by the limit

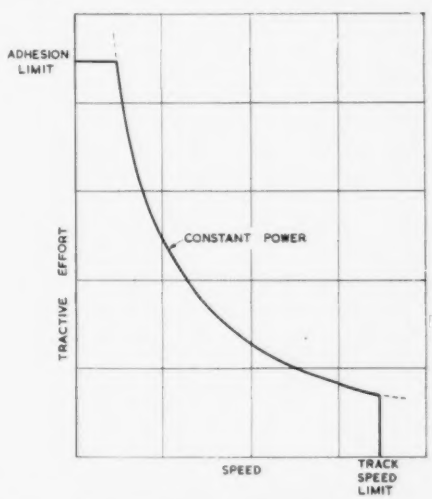


Fig. 1.—Typical diesel locomotive characteristic

TABLE I
TYPICAL DIESEL-ELECTRIC LOCOMOTIVE WEIGHTS

Country	Wheel arrangement	Power	Diesel engine weight		Locomotive weight		Engine weight
			Total	Specific	Total	Specific	Loco weight
		b.h.p.	lb	lb/h.p.	tons	lb/h.p.	%
Great Britain	C_0–C_0	2 × 1,650	2 × 9,950	6·0	106	72	8·4
U.S.A.	C_0–C_0	2,550	40,000	15·7	149·5	132	11·9
U.S.A.	C_0–C_0	1,950	33,000	16·9	103	118	14·3
U.S.A.	B_0–B_0	1,425	25,000	17·6	76	120	14·7
Republic of Ireland ..	C_0–C_0	1,200	30,350	25·3	85	158	15·9
Rhodesia	1C–C1	2,000	40,500	20·2	113	126	16·0
Queensland	C_0–C_0	1,500	31,500	21·0	87	130	16·2

of adhesion between wheels and rails, and thus ultimately by the maximum permitted axle load.

For very heavy freight trains the adhesive weight is of primary importance, but for high-speed passenger trains the greatest power possible is required within the permissible axle load. Adhesion does not present the same problem on diesel or electric locomotives as it does with steam, since most of the weight, if not all, can usually be made adhesive and the torque delivered to the driving wheels is even. Generally, the problem lies in reducing the weight of mechanical parts to accommodate a large and heavy power unit without increasing costs in using weight-carrying axles which make no contribution to adhesion. Mechanical strength must, of course, be preserved, and the scope for weight reduction is therefore limited.

High-Speed Diesel Engines

In recent years, however, the application of high-speed lightweight diesel engines to rail traction has opened a field for locomotives of total adhesion, light weight and high power. Maximum power in a locomotive of minimum gross weight compatible with adhesion requirements results in more effective work from the drawbar in proportion to the quantity of fuel used, i.e. the lower the weight/power ratio the lower is the fuel consumption for the complete train.

Conventional diesel-electric locomotives of comparatively high power are equipped with engines running at 600-1,000 r.p.m. Since the weight of a diesel engine and its associated generator is largely dependent on speed, the use of higher-speed engines can increase materially the power which can be provided within a specified locomotive weight. Moreover, any saving in weight of the power unit is, in effect, doubled by the reduction in weight of the mechanical parts ; for every ton reduction in the power-unit weight, approximately a ton can be taken from the mechanical parts.

Savings in both operating and maintenance costs result from the use of lightweight locomotives. Operating economies derive directly from the reduced weight to be moved, while reduction in maintenance costs, although less tangible, applies to both locomotives and track, since the lighter locomotive clearly results in less wear and tear.

The 3,300 h.p. locomotive described in this article, and shown as the first item in Table I, is the most powerful single-unit diesel locomotive yet built, and its weight/power ratio, 72 lb/h.p., is the best so far achieved in any diesel locomotive.

TABLE II
LEADING PARTICULARS OF LOCOMOTIVE

Total service weight* ..	106 tons
Maximum axle load	18 tons
Wheel arrangement	C_0–C_0
Track gauge	4 ft 8½ in
Length over buffers	67 ft 9 in
Width	8 ft 9½ in
Height	12 ft 10 in
Total wheelbase	58 ft 4 in
Rigid wheelbase	14 ft 4 in
Distance between bogie centres	44 ft 0 in
Wheel diameter	3 ft 7 in
Diesel-engine rating	2 × 1,650 b.h.p. at 1,500 r.p.m.
Continuous tractive effort ..	23,400 lb at 43·5 m.p.h.
Maximum service speed ..	105 m.p.h.
Fuel capacity	800 gal
Train-heating boiler capacity	2,000 lb/h
Train-heating water capacity ..	600 gal

* Including full quantities of fuel, lubricating oil, sand and train-heating water.

GENERAL DESCRIPTION

The Deltic locomotive has been designed to operate fast passenger and freight services. It has a double-cab full-width superstructure mounted on two 3-axle bogies, all axles being individually motored. The leading particulars are given in Table II.

Layout

Fig. 2 shows the layout of the locomotive. There are two diesel-generator sets with their radiator assemblies mounted in the roof above them. Between the power units there is a train-heating boiler, with the engine silencers above it and the starting batteries on either side. The driving cabs at either end are separated from the main power compartment by the control cubicles, with access doors on either side. The nose compartments contain various auxiliary machines, control gear and brake equipment. Fuel and water tanks are suspended beneath the underframe between the two bogies.

The mechanical parts, diesel engines and electrical equipment are described in later sections of this article.

Power Transmission

The electrical power circuit is shown schematically in Fig. 3. Notchless control of the power delivered to the road wheels is effected by varying the speed of the diesel engines and the field strengths of the generators and traction motors. Automatic torque regulators ensure that the electrical demand matches the available diesel-engine output under almost all conditions.

If the load does not justify the use of both engines, or in case of emergency, the locomotive may be operated with only one engine, when full tractive effort is available but corresponding speeds are reduced.

The control scheme and equipment are described in more detail later, under ' Control Gear '.

MECHANICAL PARTS

The mechanical parts comprise the underframe and superstructure, fabricated complete as one unit (Fig. 4), and the two bogies. Much care has been taken, both by refinements in design and the extensive use of light alloys, to keep weight to a minimum while maintaining ample strength.

Underframe

Main longitudinal members extend the full length of the underframe, the inner pair being fabricated flanged girders swept upwards over the bogies, while the outer pair are rolled steel channels. These longitudinals are joined by ample cross-members with strong reinforcements at the buffer beams. The underframe is plated on the top surface and set down to form wells below the power units. The plating is welded oil-tight throughout to prevent leakage to the traction motors and cables, drains being provided in the wells.

Four fuel and two boiler-feed-water tanks, suspended on flexible mountings from the underframe between the bogies, are fabricated from non-corrosive light alloy. The fuel is filtered both before entering the tanks and between the tanks and the engines. There are equalising pipes between the four tanks. The two water tanks, which are insulated and heated by a steam feed from the boiler as protection against freezing, may be filled from standard railway water columns, from other types of hose or, while the locomotive is running, from track water troughs by means of a pick-up device operational in either direction of travel. To avoid damage by excessive pressure from direct filling, the water is first fed into an open trough from which it flows by gravity into the tanks.

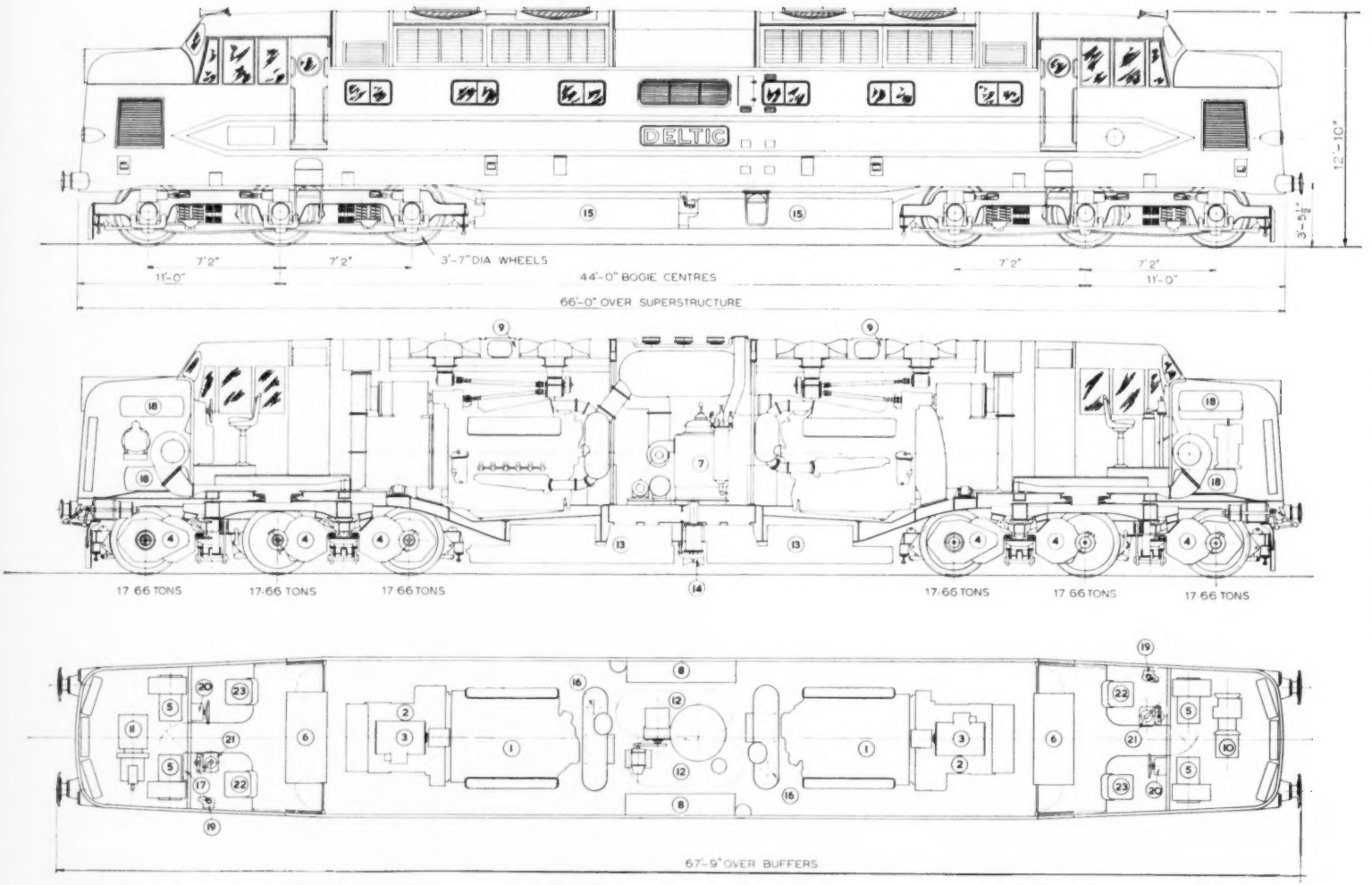
Storage for sand, lubricating oil and engine coolant is provided in 12 sealed-off compartments between the outer and inner members of the underframe. These are filled from the body sides.

Superstructure

The complete superstructure, comprising power compartment, cabs and nose compartments, is fabricated from rolled-steel sections with panelling attached by arc-welding. Light alloys are used for the removable roof sections, doors, louvres, tread plates and much of the pipework, conduit and ducting.

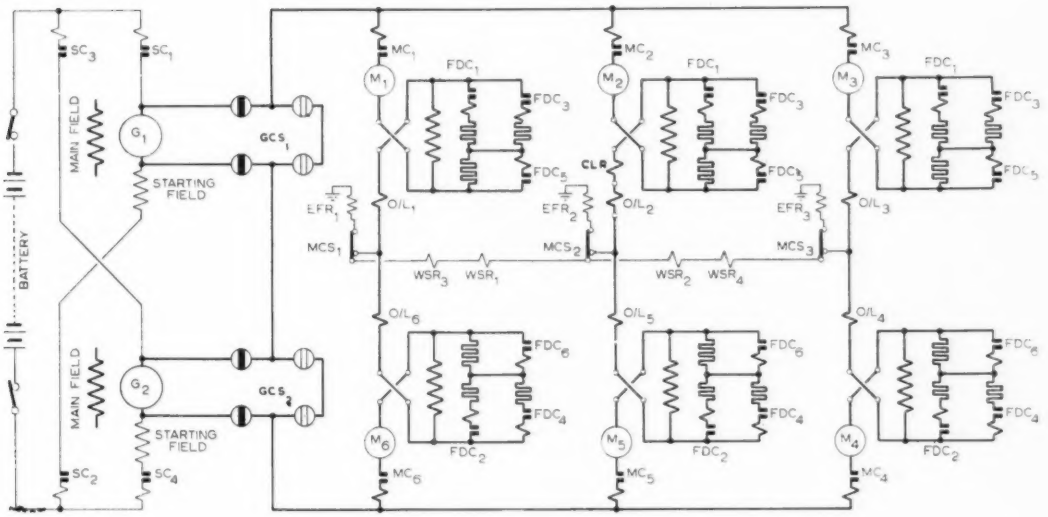
Main Power Compartment

The removable roof sections above the major items of equipment enable the latter to be lifted



1. Diesel engine
2. Main generator
3. Auxiliary generator
4. Traction motor
5. Traction-motor blower
6. Control cubicle
7. Heating boiler
8. Battery
9. Radiator
10. Air compressor
11. Exhauster
12. Silencer
13. Water tank
14. Water pick-up
15. Fuel tank
16. Fuel pump
17. Air-brake equipment
18. Air reservoir
19. Air-brake valve
20. Hand brake
21. Controller
22. Driver's seat
23. Assistant's seat

Fig. 2.—General arrangement of Deltic 3,300 b.h.p. 106-ton diesel-electric locomotive



$SC_{1,2,3,4}$	Starting contactors	CLR	Current-limit relay
$G_{1,2}$	Main generators	$EFR_{1,2,3}$	Earth-fault relays
$GCS_{1,2}$	Generator cut-out switches	$O\,L_{1,2,3,4,5,6}$	Overload relays
$M_{1,2,3,4,5,6}$	Traction motors	$MCS_{1,2,3}$	Traction-motor cut-out switches
$MC_{1,2,3,4,5,6}$	Traction-motor contactors	$WSR_{1,2}$	Wheel-slip relays (first stage)
$FDC_{1,2,3,4,5,6}$	Traction-motor field contactors	$WSR_{3,4}$	Wheel-slip relays (second stage)

Fig. 3.—Power schematic diagram

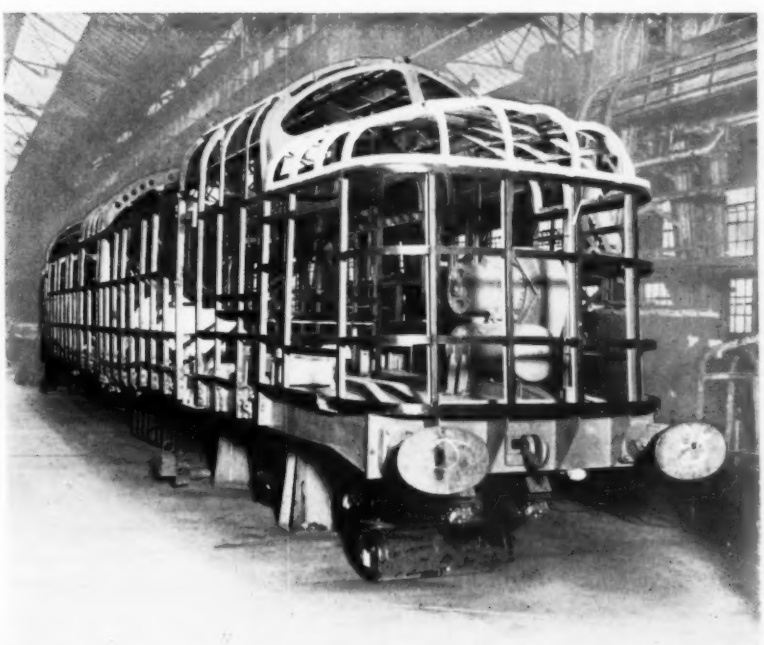


Fig. 4.—Fabricated underframe and superstructure

Fig. 2.—General arrangement of Deltic 3,300 b.h.p. 100-ton diesel-electric locomotive

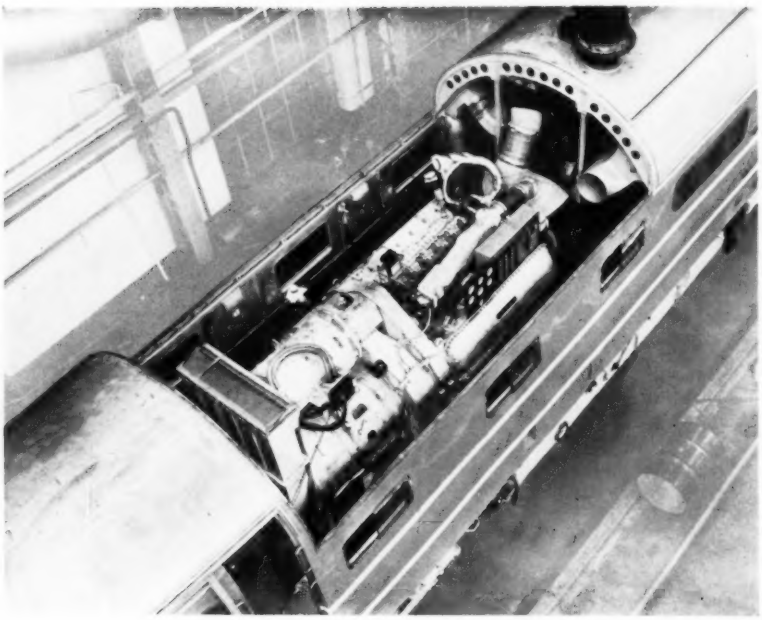


Fig. 5.
Roof section removed above power unit

out when necessary (Fig. 5). The greater part of the roof is formed to a box section and houses the radiators and ancillary equipment for cooling the engine circulating water and lubricating oil. Access for maintenance of this equipment is obtained via hinged doors both above and below.

The interior finish of the body sides comprises panels of expanded ebonite between thin light-alloy sheeting, these panels being spaced from the felt-sheet lining of the outer skin. This construction provides a considerable degree of sound proofing.

Louvred intakes, with filters as necessary, are provided in the body sides and roof for the combustion air required for the engines and boiler and the cooling air for the radiators.

Cabs

Each cab (Fig. 6) has two entrance doors, access doors either side of a centrally mounted control cubicle to the gangways through the power compartment, and a further access door in the front bulkhead to the nose compartment. The forward observation windows are made of armour-plate glass, and sliding windows are provided on either side. Each cab has upholstered seats for the driver and his assistant, cab heaters beneath each footrest, and a boiling ring. The interior finish is in light-alloy panelling on the walls and hardboard panelling for the roof, the whole being enamelled.

The driving position is on the left-hand side of the cab, the master controller and train vacuum-brake valve being set to the driver's right and the independent locomotive air-brake valve to the left ; an instrument panel and indicator lights are mounted on the facing bulkhead.

Operation of the master controller varies the power delivered to the road wheels, as described later under ' Control Gear '. The vacuum-brake valve operates the train brakes directly and the locomotive air brakes through a proportional valve. The air-brake valve operates the locomotive brakes only.

The instruments comprise a speedometer, two generator voltmeters, main ammeter and three duplex gauges for the compressed air and vacuum systems. One indicator light for each engine and one for each pair of traction-motor blowers glow dimly when the respective machines are operating and brightly if they shut down. Gauges for the train-heating boiler, the water pick-up scoop

control and the hand wheel for the parking brake are mounted in front of the assistant driver's seat. Other controls include engine start and stop buttons, horn button, sanding valve, etc.

Nose Compartments

The nose compartments have louvred and filtered air intakes either side for the traction-motor blowers and compressor ; the light-alloy roof is removable to permit lifting of the auxiliary machines when necessary.

Bogies

The bogies, each of which has three motored axles, are of the equalised type with swing bolsters.

The superstructure load is carried on four side bearers on each bogie bolster and is transmitted through double-elliptic laminated springs to spring planks suspended by long swing-links from the bogie frame. From here the load is distributed through four sets of helical springs to equalising beams under-slung from the axle boxes.

Fig. 6.—Driver's cab, with master controller and train vacuum-brake valve to right of seat, and locomotive air-brake valve to left

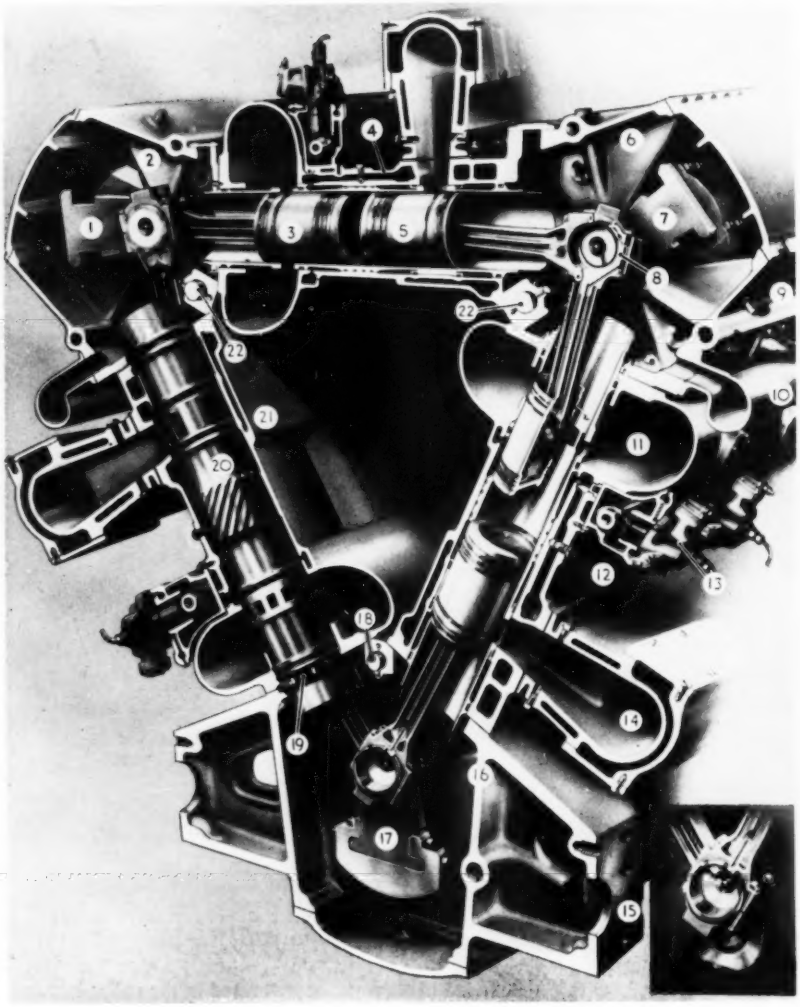
The bogie frames are of fabricated construction, the side members being of box section with the transoms and head-stocks riveted, with gusset reinforcement, to them. Traction motor nose suspension brackets on the transoms are arranged for easy removal so that the motor and wheel set can be dropped out of the bogie without having to tilt the motor.

The bolsters are also of fabricated construction and have rubber pads incorporated in the side bearers for insulation against vibration and sound. Cooling air for the traction motors passes through the hollow bogie centre into the bolster and thence through leather-bellows connections to the motors.

Forged-steel equalising beams are of straight I section to reduce unsprung weight. They are carried in stirrups incorporated in the roller-bearing axle boxes. The road wheels are of solid-disc type. Manganese-steel liners are fitted to the axle boxes, guide faces, bolster rubbing faces, side bearers and centre pivots. Liners are also fitted to the axle-box stirrups and the ends of the equalising beams.

Braking and Sanding

Independent high-pressure air-brake cylinders operate clasp brakes on each wheel, these cylinders being mounted above each axle box outside the bogie frame, for easy access. The brakes on one pair of wheels on each bogie may be operated manually from the adjacent driving cab for parking.



1. 'BC' crankshaft
2. 'BC' crankcase
3. Inlet piston
4. 'B' cylinder block
5. Exhaust piston
6. 'AB' crankcase
7. 'AB' crankshaft
8. Connecting rod
9. Crankcase tie-bolt
10. Drain-oil manifold
11. Air-inlet manifold
12. 'A' cylinder block
13. Fuel-injection pump
14. Exhaust manifold
15. Engine mounting face
16. 'CA' crankcase
17. 'CA' crankshaft
18. Pump-drive shaft
19. Castellated ring-nut
20. Cylinder liner
21. 'C' cylinder block
22. Blower drive shafts

Fig. 7.—Section through diesel engine

Sand stored in compartments in the underframe is delivered to the leading wheels of each bogie, according to the direction of travel, through flexible pipes to allow for bogie movement. Pneumatic ejectors are mounted on the underframe.

DIESEL ENGINES

Power for the locomotive is provided by two Napier 18-cylinder Deltic engines each direct-coupled to its associated main generator. Particulars of the engine are given in Table III and a sectional view is shown in Fig. 7.

Background

The design of the Deltic engine, to an Admiralty specification for fast patrol boats, began in 1946. For this application the engine has a rating of 2,500 b.h.p. at 2,000 r.p.m., this being based on a period of 1,000 hours between piston withdrawals for ring replacements.

TABLE III

LEADING PARTICULARS OF DIESEL ENGINE

Output (at continuous rating)	1,650 b.h.p.
Number of cylinders	18
Bore of cylinders	5·125 in
Stroke	2 × 7·25 in
Overall length	94 in
Overall height	90 in
Overall width	75 in
Crankshaft speed	1,500 r.p.m.
Piston speed	1,812 ft/min
Brake mean effective pressure	80·9 lb/in²
Fuel consumption	0·377 lb/b.h.p./h
Lubricating-oil consumption	5 pints/h
Dry weight*	9,950 lb

* This weight includes mounting feet but excludes exhaust system.

For rail traction, where the duties are very different and a longer period between piston withdrawals is required, a rating of 1,650 b.h.p. at 1,500 r.p.m. was chosen. This was based on a minimum period of 5,000 hours between piston withdrawals, but it is hoped that, as a result of improvements arising from service experience, it may be possible to increase this to 10,000 hours.

Basic Design

The two main factors contributing to the good qualities of the engine are the use of the opposed-piston principle and the disposition of the engine in the form of an inverted equilateral triangle. Thus the engine consists in effect of a combination of three single-bank opposed-piston engines using three common crankshafts, one at each apex of the triangle, as shown in Fig. 7.

The opposed-piston design was selected because it provides efficient ' end to end ' scavenging of the cylinders, avoids the use of valve gear and dispenses with cylinder-head sealing. These advantages are enhanced by the triangular configuration, which makes a structure of great inherent rigidity and permits the compact grouping of small cylinders, thus combining the advantages of short engine length and low weight per horsepower. The vibration characteristics of this arrangement are good, the out-of-balance forces and couples being negligible while torsionals are completely absent in the running range.

Mounting of Power Unit

Each engine-generator set is resiliently mounted on the locomotive underframe at three points, one either side of the lower crankcase of the engine and the third beneath the generator.

Construction

The basic engine structure comprises three crankcases and three cylinder blocks, the six units being secured together by high-tensile-steel bolts which clamp each cylinder block between its associated crankcases and also take all the combustion stresses.

Crankcase and Main Bearings

Each crankcase is a one-piece alloy casting, substantially webbed and carrying a crankshaft in thin-wall lead-bronze lead-plated main bearings. Each bearing cap is secured by four studs and is located in addition by a tie bolt passing transversely through it and the crankcase walls on either side. The two upper crankcases are identical, but the lower one is deepened in section to carry engine bearers and to provide oil drainage for the dry-sump lubrication system. The lower crankcase also carries the oil pumps and water pump.

Crankshafts

The two upper crankshafts are identical and rotate clockwise viewed from the free end, while the lower one has opposite-hand throws and rotates anti-clockwise to obtain the correct phase relationship. The crankshafts are machined from steel-alloy forgings and are nitrided all over, the bearing surfaces being finished by lapping. Each crankshaft is statically balanced and fitted with a viscous-type torsional vibration damper. Owing to their comparatively short length, the crankshafts have good torsional rigidity.

Cylinder Blocks

The three cylinder blocks are identical light-alloy monobloc castings with integrally cast coolant passages, exhaust ports and air-inlet ducts.

Cylinder Liners

Machined from hollow steel forgings, the cylinders are of the ' wet ' type. The bores are chromium plated, dimple etched and finished by lapping. Longitudinal location is provided by a ring nut, which clamps a flange on one end of the liner against a shoulder in the bore of the cylinder block. Radial location is effected by the injector adaptor, which is screwed through the cylinder block into the wall of the liner.

Pistons

Each piston comprises an outer body and inner gudgeon pin housing, the two being held together by a circlip. The outer body itself is in two parts, a bronze head carrying two compression rings being screwed into a lower part of aluminium alloy carrying a third compression ring and the three scraper rings. The inner member is machined from a high-strength aluminium alloy forging and carries the fully-floating hardened steel gudgeon pin. When assembled, these parts form passages behind the piston rings in which lubricating oil is circulated by the piston motion to assist cooling.

Connecting Rods

Each crankpin carries a pair of forged alloy-steel fork-and-blade connecting rods on thin-wall lead-bronze lead-plated bearings. The exhaust piston is attached to the forked rod which carries a nitrided-steel bearing shell containing the thin-wall bearing for the crankpin. The inlet piston is attached to the blade or plain rod which carries a thin-wall bearing moving on the outside of the steel shell held by the forked rod.

Camshafts

The injection-pump camshafts are enclosed by light-alloy casings assembled to the outer faces of the cylinder blocks. They are carried in phosphor-bronze bearings lined with white metal, and are driven through bevel gearing and short quill-shafts from the crankshaft. The quill shafts incorporate simple vernier timing adjustments.

Phasing Gear

Power is transmitted from the three crankshafts through coupling quill-shafts to phasing gears which combine the three outputs into a single main output shaft. Idler gears determine the direction of rotation. The phasing gear also drives an auxiliary power take-off shaft and the engine governor.

Scavenge Air Blower

A double-sided single-stage centrifugal blower, mounted on the free end of the engine and driven through flexible shafts from the upper crankshafts, provides an air flow which completely scavenges the combustion chambers and provides a degree of supercharging.

Injection System

Fuel is supplied to the injector in each cylinder by an individual constant-stroke variable-delivery injection pump. The pumps for each cylinder block are supplied with fuel from a common pressurised fuel line in a system which precludes air locks. Any one pump can be removed and replaced by another, correct timing and matching being obtained automatically.

Lubrication System

Lubrication is on the dry-sump principle with a main oil tank incorporated in the underframe. A pressure pump delivers oil from this tank through twin full-flow filters to all bearings and gears throughout the engine, and the drain oil is returned by a scavenge pump via the roof-mounted radiators. Oil for cooling the pistons passes from the crankshaft through drillings in the connecting rods and gudgeon-pin housing, and is afterwards discharged through drain holes to the crankcases. The oil flow to the scavenge blower bearings is controlled by a metering pump.

Cooling System

Cooling of the engine, apart from the oil cooling of the pistons just described, is by circulation of an inhibited water coolant. A pump, mounted on the lower crankcase at the free end, circulates the coolant round the cylinder blocks, through a thermostatic valve to the roof-mounted radiators or a by-pass and so back to the pump intake. A hand transfer pump is fitted to enable the header tank to be replenished from the reserve tank in the underframe.

GENERATORS AND TRACTION MOTORS

Main Generators

Each of the two main generators is flange mounted to its associated diesel engine, the armature shaft being directly coupled to the engine output shaft, the coupling forming also the hub of the generator cooling fan. The armature is supported by a self-aligning roller bearing at the commutator end and by the final drive bearing in the engine phasing box at the other.

The field system comprises six main poles, six interpoles and a compensating winding. The main poles have two windings, one separately excited from the auxiliary generator under the control of the torque regulator, and the other, used only when motoring the generator to start the engine, series excited.

Auxiliary Generators

Auxiliary generators, mounted above each main generator, are conventional 4-pole machines providing a constant 110-volt supply for main-generator excitation, auxiliary machines, control gear, lighting, heating and other services. They are driven from the engine phasing box at a speed 1·68 times that of the main generator ; in normal operation the load is shared between the two, but either can carry the full auxiliary load with only one engine running.

Traction Motors

The six traction motors, three to each bogie, are axle-hung and nose-suspended, the suspension bearings being of the white-metal sleeve type. The drive to the road wheels is through straight spur gearing with a ratio of 59 : 21. The motors are force-ventilated 6-pole series machines with lap-wound armatures. Field weakening in two stages down to 50% for two engine working or 30% for single engine working is obtained by shunting the field windings with suitable resistors.

CONTROL GEAR

The bulk of the control gear, apart from the actual driving controls in the cab, is housed in the two cubicles forming the partitions between the cabs and main power compartment, and in the nose ends.

Power Control

Operation of either of the two master controllers by the driver sets the power circuits, and controls the power delivered to the road wheels. The master controllers each have two operating handles—a ' master switch handle ' and a ' control handle '—but only one ' master key ' for locking both controllers.

The master switch handle has four positions, namely ' off ', ' forward ', ' engine only ' and ' reverse '. In the ' engine only ' position, the diesel engines may be started and their speeds regulated for testing, etc., but the main power circuits are not completed. With the master switch handle in the ' forward ' or ' reverse ' positions, initial control-handle movement completes the power circuits, after which further movement steadily increases the power output from the generators.

Mechanical interlocking ensures that the master key can be inserted or withdrawn only when both handles are at ' off ', and also that the master switch handle can be moved only when the control handle is at ' off '.

The control handle itself has two marked positions, namely ' off ' and ' 1 '. The power circuits are made in notch ' 1 ' and further movement provides notchless control. Cam-operated contacts set the power circuits, but power is controlled by a self-lapping air valve in the controller base which varies the air pressure to an actuator on the engine governor. This hydraulic governor so controls the fuel admission that the maximum permissible torque at any given engine speed is not exceeded. The governor law for the engine is shown in Fig. 9. Cam-operated switches on the governor detect any over- or under-loading of the engine and initiate correction by variation of generator field strength by the torque regulator. Engine speed is not affected by the first part of the control-handle movement, and the governor switches only are operated to increase the generator field strength, thus giving a very fine control in the lower power range. Having thus built up to the maximum power obtainable at the idling speed of the engines, further movement of the control handle steadily increases the diesel-engine speed, while the torque regulator, under the control of the governor switches, ensures that the generator and traction-motor field strengths are adjusted to match the electrical load to the available engine output. This system gives smooth control of the power delivered to the road wheels under all conditions, and, since the diesel engines are operating always at the lowest speed commensurate with the power required, engine wear is kept to a minimum.

Torque Regulator

Each power unit has its own torque regulator, and the two operate independently of one another.

The regulator comprises essentially a series of contacts arranged concentrically round a motor-driven shaft carrying an arm with a roller which closes the contacts in turn thus progressively cutting out, or introducing, resistance in the main-generator field circuit. When all resistance has been cut out, other contacts operated by cams on the regulator shaft introduce field weakening of the traction motors. The corresponding pair of these latter contacts on each of the two regulators are in series, so that field weakening of the traction motors can be introduced only if the load on both diesel engines permits. Further contacts at each end of the main system act as limit switches to stop the regulator driving motor.

The regulator-motor field is permanently excited, while the armature is fed by a circuit through the governor switches, which, by controlling the polarity of the supply, cause the armature to rotate in the appropriate direction to initiate strengthening or weakening of the main-generator field.

Protective Devices

Wheel Slip

Protection against wheel slip is provided in three stages. The arrangement of the six traction motors in three parallel strings of two in series with the mid-points linked inherently reduces tendency to slip. However, if slip does occur, current relays in each equaliser link apply corrective action in two stages. Normally there will be no current in the equaliser links, but slip will cause a small current to circulate and operate one of the relays, sounding an alarm in the cab and reducing the field strength of the main generators. Increased slip will operate the second relay, opening the traction circuits and reducing the speeds of the diesel engines to idling. In the latter case the driver must return the control handle to ' off ' before power can be restored.

Engine

A series of pressure- and temperature-operated switches protects each engine from loss of lubricating-oil pressure, high temperature of coolant and low level of coolant. A pressure switch incorporated in the governor ensures that the engine cannot run below its minimum designed speed while on load.

Electrical

The main power circuits are protected by overload relays, three with current coils only and three with current and earth-fault coils. The relays open the main-generator field circuits and traction-motor contactors, and reduce the diesel-engine speed to idling.

Warning lamps in the cab glow brightly if the traction-motor blowers cease running.

Fire

Detectors, mounted at various points in the locomotive roof, give audible indication in the cab of a sudden increase in temperature caused by fire. If this cannot be controlled by the hand extinguishers, operation of a handle in the driver's cab sprays the locomotive body throughout with carbon dioxide released from jets in the roof, fed from bottles mounted in either end of the main power compartment.

Cut-Out Switches

Generator

Manually-operated cam-type group switches normally connect the two main generators in series, but, to operate the locomotive on only one power unit, the cut-out switch of the other generator is thrown to provide a by-pass circuit, the remaining power unit feeding all six traction motors to deliver full tractive effort although at a reduced locomotive speed.

Normally the auxiliary load is shared between the two auxiliary generators, but with only one power unit operating, all the auxiliary load is transferred to the active auxiliary generator by means of contacts on the cut-out switch.

The cut-out switches are interlocked so that they can be operated only with the master controller at ' off '.

Traction Motor

In the event of a fault on a traction motor, a pair of motors may be isolated from the equaliser link by operation of a blade-type cut-out switch. Auxiliary contacts on this switch interrupt the circuit to the associated motor contactors.

AUXILIARY EQUIPMENT

Electrically Driven Auxiliaries

Compressor

A motor-driven reciprocating compressor mounted in No. 1 nose end supplies air for operation of the locomotive brakes, sanders, control gear, horns, etc. The compressor motor is automatically switched off or on as required under the control of a compressor governor.

Exhauster

Vacuum for the train brakes is maintained by a continuously-running 2-speed motor-driven rotary exhauster mounted in No. 2 nose end ; the higher speed assists in quick brake release. If, when the locomotive is operating normally with both power units, the unit supplying the exhauster motor shuts down under fault conditions, an arrangement of change-over contactors automatically switches the exhauster motor to the active auxiliary generator.

Traction-Motor Blowers

Two traction-motor blowers are mounted in each nose end of the locomotive, each pair supplying air to the three traction motors in the adjacent bogie and one main generator. External cooling air is drawn through filters in the locomotive body sides.

Miscellaneous Small Electrical Machines

Various small motors drive the fuel-supply pumps, torque regulators, train-heating-boiler auxiliaries and cab-heater fans.

Radiator-Fan Drives

Two roof-mounted radiator fans for each engine are driven from their respective engines through a system of gears and shafts, with centrifugal clutches to reduce the inertia load.

Train-Heating Boiler

Steam for train heating is generated in a few minutes from cold by an oil-fired boiler with a maximum capacity of 2,000 lb/h, automatic control maintaining a steam pressure of between 70 and 80 lb/in². Compressed air is used for atomisation of the fuel, while the blower, fuel pump, water pump and ignition are operated electrically.

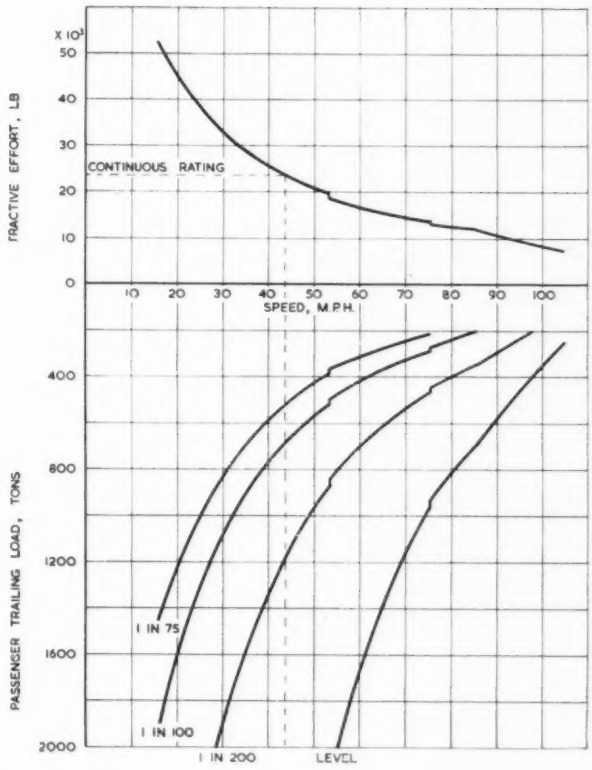
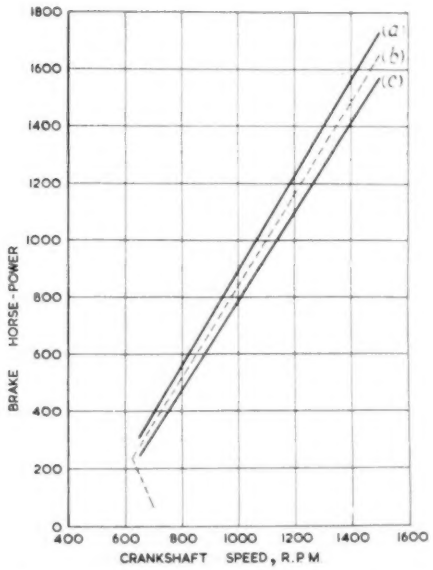


Fig. 8.—Locomotive performance curves, both engines operating

PERFORMANCE

The performance particulars of the complete locomotive with both engines running are given in Fig. 8. The upper portion shows the tractive effort available at various road speeds, the effort being limited by strength of the drawbar rather than adhesion or electrical characteristics. The lower part indicates the trailing loads which may be worked on various gradients, these curves being based on values of locomotive and train resistance determined by the dynamometer-car trials.

The locomotive characteristic is, in effect, a combination of the characteristics of the prime mover and the transmission. Figs. 9-11 give these



(*a*) Upper limit (*b*) Mid law (*c*) Lower limit

Fig. 9.—Diesel-engine governor law

characteristics for the diesel engine, main generator and traction motor respectively. It may be seen from Fig. 9 that the governor law permits variation of engine power at any given speed within certain set limits. The 'mid law' figures, with the auxiliary load power subtracted, have been used in deriving the other curves. The utilisation of engine power is shown schematically in Fig. 12.

Operating on one power unit, the locomotive performance is not directly proportional to that shown in Fig. 8, since the field weakening of the traction motors is altered to raise the road speed corresponding to the unloading point of the main generator.

SUMMARY OF SERVICE 1955-58

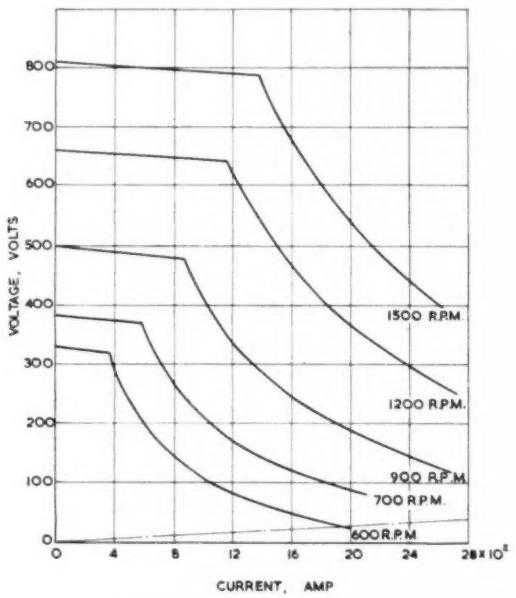
The locomotive entered traction service on British Railways in October 1955, and from then until August 1956 was principally engaged in working fast freight trains at night between Liverpool and London. A series of dynamometer-car trials was carried out in August and September 1956 between Carlisle and Skipton.

On completion of the trials, the locomotive entered passenger service between London and Liverpool, working 'The Merseyside Express' to London and 'The Shamrock' on the return journey, and at the turn of the year it commenced working passenger trains from London to Carlisle during the day, returning with sleeper trains at night.

In May 1957 it reverted to the London-Liverpool service, and a month later the schedule was changed to permit the addition of a round trip between London and Crewe daily. This working continued until February 1959 and involved a total of some 700 miles running per day. The locomotive has since been transferred to the Eastern Region where it has continued trials prior to the delivery of 22 production-version locomotives to that system.

OPERATING EXPERIENCE

The prototype locomotive was built essentially to prove that two powerful diesel engines may be



Speed r.p.m.	*Net input power, h.p.*
1,500	1,563
1,200	1,083
900	594
700	318
600	178

Fig. 10.—Generator output curves

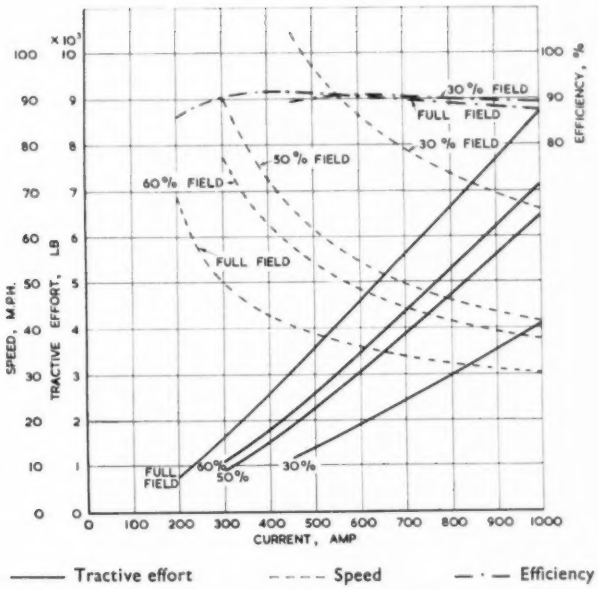


Fig. 11.—Traction-motor characteristic

used in one unit as made possible with the Deltic engines. Other developments were incorporated, some of which have proved sound in service while others have had to be modified or abandoned. Such trials were useful but, of course, have taken time, involving withdrawal from service on a number of occasions additional to those arising from normal maintenance requirements. In this section some of the principal problems and the modifications carried out are discussed.

Single-Engine Operation

The original concept of the locomotive provided for operation with both diesel engines running, except in case of emergency. No provision was made for changing the transmission characteristics to suit the reduced power available when operating on one engine, and the connection of the auxiliary loading was such that, for example, the traction-motor blowers could operate only at about half their normal speed.

Operating experience soon indicated that it would be preferable and more economic to work certain services with only one engine running. It was therefore decided to make a major electrical modification permitting single-engine operation with all six traction motors as a normal and efficient feature.

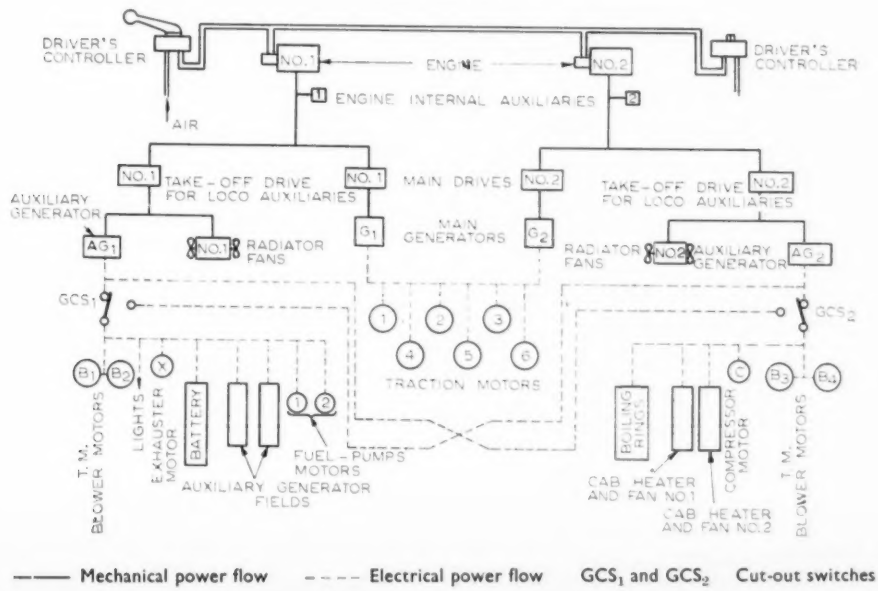


Fig. 12.—Utilization of engine power

The main power circuits were not greatly affected, because they had been designed originally to permit single-engine operation, but, since the total voltage would be approximately halved, it was necessary to change the traction-motor field-diverting resistances to give a top locomotive speed of about 70-75 m.p.h. with a reasonable trailing load. The necessary switching was interlocked with the main generator cut-out switches, thus providing automatic circuit changes.

Major alterations were necessary also to the auxiliary circuits to enable all four traction-motor blowers and other auxiliary equipment to be fed from either of the two auxiliary generators.

Mechanical Parts

Wheels

After running some 12,500 miles, 'shelling' of the treads of the solid disc wheels reached a condition in which they required turning. The thermal effects of the non-ferrous brake blocks then in use became suspect as the cause of shelling, and after the turning of the wheels the locomotive was returned to service with cast-iron brake blocks, but these showed no improvement. The wheels were turned twice subsequently and afterwards settled down to a normal condition to run an additional 105,000 miles before turning. No explanation has emerged as to the irregular performance of the wheels during the early part of their service when they were braked by both non-ferrous and cast-iron blocks.

Shock Absorbers

Although the locomotive rides well, periods of vertical oscillation at about 12 and 52 m.p.h. were noticeable during acceleration. This was not sufficiently serious to warrant modifications, but hydraulic shock absorbers have been fitted for trial to obtain basic information towards perfecting the riding qualities of the locomotive. The shock absorbers are fitted four per bogie, between the equaliser beams and the bogie frames.

Air Ducting

In the course of the 200 hours of static test running, fatigue cracking appeared in the engine air-inlet duct, the associated filters and the locomotive body side. These parts were strengthened before the locomotive entered service. The fatigue was caused by the combined effect of high-frequency vibrations within the locomotive structure and pulsations in the engine intake air, and persisted after the locomotive entered service. On two occasions pieces of fractured ducting entered the engines, causing failure, and generally the problem became so troublesome, even after further modification, that the ducting was disconnected and the engine air was drawn from the engine room. This was not satisfactory since the engine room temperature increased considerably, air pulsations created discomfort, and the increase of ambient temperature affected adversely the performance of the train-heating boiler. Eventually, air ducting of a completely new design was fitted and proved satisfactory.

Diesel Engines

The diesel engines have required very little routine maintenance and have been remarkably free from the many mechanical troubles commonly experienced when diesel engines are first applied to trail traction.

Carbon Formation

During the early period of operation on fast freight trains between Liverpool and London, when the engines were very lightly loaded, the exhausts were dirty in the idling-speed range and carbon sparks were emitted when load was applied. The pistons originally fitted were known to have excessive clearance for the traction rating of the engine, and these were therefore replaced by pistons with reduced clearance and modified oil-scraper arrangements. Although this change effected some improvement, the exhausts were still dirty under certain conditions.

A new type of piston with a bronze head and different form of combustion chamber had been under development for some time. Following successful trials on the test bed, pistons of this type were fitted to the engines, and combustion conditions were improved over the whole operating range. The quality of the exhaust is now acceptable, and further improvements are expected to result from later versions of this piston design.

Engine Stalling

In the course of early trial running the engines showed a tendency to stall if they were throttled back very rapidly. Tests showed this to be due to

temporary overloading which occurred because of the inherent delay in the reduction of the generator field by the torque regulator. This trouble disappeared when—principally to improve the tractive effort graduation—minor modifications were made to the generator field resistance circuits and the controller air valves.

Miscellaneous

Wheel Slip

The operation of the devices for protection against wheel slip has been explained under 'Control Gear'. In the course of early trials of the locomotive it was found that the detection circuits were too sensitive, so that warning was given when no wheel slip occurred. The small out-of-balance currents in the equalizer which caused operation of the relays were probably due to slight mechanical and electrical disparities between the different traction motors and wheels. After resetting the relays to operate with somewhat higher circulating currents, the system operated satisfactorily, but, after some time in service, the Post Office-type relays used proved unsuitable in the operating conditions inseparable from locomotive work and were replaced by more robust current-operated units.

Maximum Speed

The maximum road speed as originally designed was 90 m.p.h. It soon became apparent that this was too low for a locomotive of this type and the gear ratio of the traction motors was changed to permit a maximum running speed of 105 m.p.h. This entailed resetting the overload relays and recalibrating the driving ammeter, since the former were set and the latter calibrated to ensure that the locomotive could not exert a tractive effort greater than that permissible for the draw gear.

Gear Cases

The gear cases as originally fitted were designed and made in accordance with practice established after many years of experience, mainly with vehicles equipped with axle-hung traction motors for operation at maximum speeds up to 75 m.p.h. The motors themselves have withstood satisfactorily the considerably higher speeds of the Deltic locomotive, but after 180,000 miles of service, fatigue cracks appeared in the gear cases and their fixing bolts. The gear cases have been strengthened generally, the bolts being replaced in high-tensile steel.

Train-heating Boiler

As originally fitted, air for the train-heating boiler was drawn from outside the locomotive, but as the intake was adjacent to the engine air intakes, air starvation occurred owing to the engines taking most of the available air under certain circumstances. The duct to the outside of the locomotive was therefore removed and a new intake provided for the boiler to draw air from inside the engine room. This arrangement was not entirely satisfactory, and it was therefore decided to revert to the original system of drawing combustion air from outside the locomotive. For this purpose two new louvres were fitted in the locomotive roof well clear of the engine air intakes.

Since the boiler was originally installed, the manufacturers have made a number of improvements to the model, and these have been applied during the course of summer overhauls.

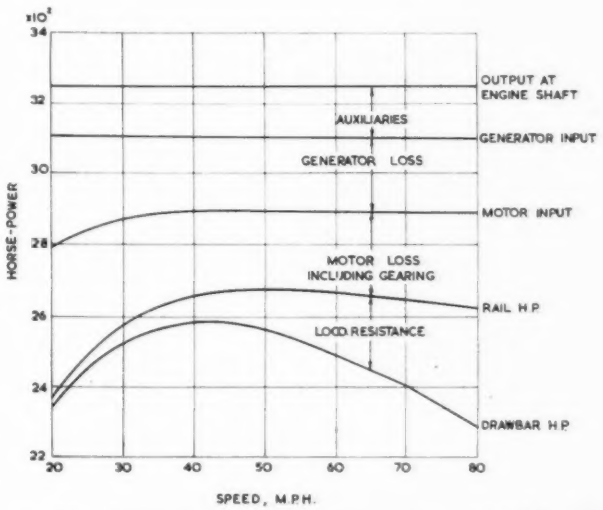


Fig. 13.—Power distribution from two engines at 1,500 r.p.m. (From B.T.C. Test Bulletin)

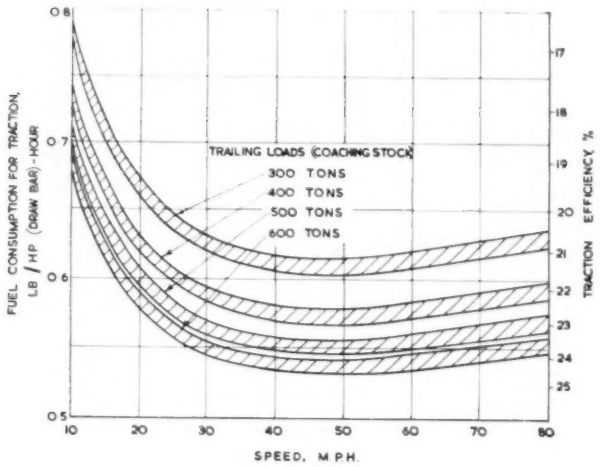


Fig. 14.—*Maximum traction efficiency for various loads with two engines* (*From B.T.C. Test Bulletin*)

PERFORMANCE AND EFFICIENCY TESTS

In August and September 1956 a series of performance and efficiency tests on the locomotive was carried out on the Carlisle-Skipton route, using the mobile test plant of the London Midland Region of British Railways. A dynamometer car was coupled directly to the locomotive and the necessary loading was provided, in most cases, by up to three mobile test units coupled in rear. A very comprehensive series of tests was carried out, and has been fully described elsewhere.*

Figs. 13 and 14 are typical of the results. Fig. 13 shows the distribution of power at various road speeds with both engines delivering full power, while Fig. 14 shows the overall thermal efficiency under various load conditions. The bands on Fig. 14 correspond to the maximum traction efficiency for the various loads, the upper and lower limits being within 2% of the minimum fuel per available draw-bar power at any speed.

In some runs a load of 642 tons comprising 20 coaches was hauled by the locomotive, and, so far as possible within road limits, the maximum power from both engines was sustained throughout. The actual sustained draw-bar power was about 2,200 h.p. and the average speed on a 15-miles gradient of 1 in 100 was 56 m.p.h. with a minimum of 50 m.p.h.

CONCLUSION

In accumulating over 200,000 miles in service, much has been learned from the operation of the prototype Deltic locomotive. It has been engaged on a variety of duties, including the working of some of the heaviest and fastest express passenger trains on British Railways, and it has also undergone an exhaustive series of performance and efficiency tests.

The concept of installing sufficient power in a single-unit diesel locomotive, complying with restrictive axle loads and load gauges, to work any trains operating on British Railways has been confirmed. In fact, on many occasions the reserve of power has been used to good effect in making up time lost due to permanent-way slacks, signal checks and other causes.

Being essentially a development of advanced design on which several novel schemes have been tried out, the locomotive has, inevitably, suffered from a number of initial troubles, but on no occasion has it failed completely on the open line. The valuable experience gained has suggested a number of improvements which will be embodied in further similar locomotives shortly to be built.

ACKNOWLEDGMENTS

The production of the complete Deltic locomotive follows much research and planning over a long period of time, and a satisfactory achievement has been possible only as a result of the effort of a number of persons working together as a team. In this context the author records his gratitude to those friends and colleagues of the English Electric Group who have so generously assisted in the preparation of the paper. Appreciation is due to British Railways for co-operation and

* *Performance and Efficiency Tests—English Electric 'Deltic' 3,300 h.p. C_0-C_0 Diesel Electric Locomotive.* British Transport Commission Bulletin No. 19.

assistance in running the locomotive and for permission to make use of information concerning the dynamometer-car trials.

Finally, the author is grateful to Sir George Nelson, Bt., Chairman of The English Electric Company, for permission to publish the paper, and to the Institution of Electrical Engineers for permission to reproduce it in this journal.

The Masons Mill substation of the Union of South Africa Electricity Suppl
circuit-breakers, solenoid operated

This substation couples the Commission's 132 and 88 kV systems and also k
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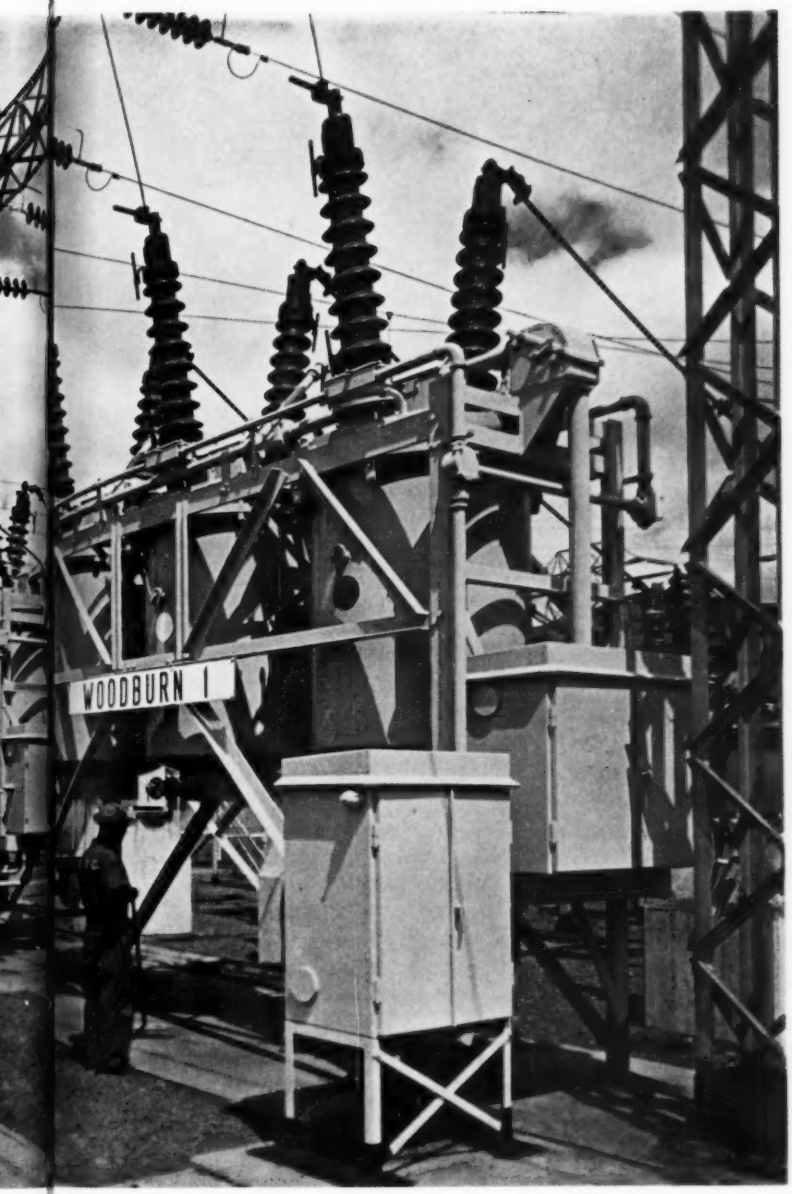

Suppon, equipped with 'English Electric' 88 kV 1,500 MVA Type OKG7 bulk-oil

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Non-destructive Testing in Electrical Engineering

By D. J. GRIFFITHS, A.M.I.E.I., A.N.D.T.S., Works Radiologist, Stafford.

THE PRESENT-DAY insistence upon higher and still higher stresses, and the criteria of near-perfection necessitated by nuclear engineering, have necessarily increased the need for various types of inspection, and today in every manufacturing organisation some form of quality control is practised.

One clearly defined section of quality control is non-destructive testing. Despite the tendency to relate this term solely to those tests that are metallurgical in nature, for example, radiography or ultrasonic flaw detection, it should not be forgotten that there are many other testing methods which do not require the destruction of the specimen. Examples of this kind of test, peculiar to the electrical engineering industry, which may be quoted are the taking of electrical discharge measurements and loss measurements on inductive apparatus, such as transformers.

This article deals mainly with the ' metallurgical ' methods of inspection. These methods find widespread use, not only in the control of quality—the ' trouble-shooting ' inspections intended to reveal hidden defects—but also in investigational and development work.

Radiography

Although not the oldest, radiography is one of the most widely used non-destructive tests, and its popularity can perhaps be traced directly to the possibility of application to a wider range of materials than most other tests, and also to the fact that it is, at present, the only method which will provide a permanent pictorial record of the conditions obtaining within the examined object. From the date of Röntgen's discovery of X-rays this latter facility was realised by the medical profession, and the only reason for the delay in putting X-rays to work in the factory was the lack of sufficiently powerful X-ray tubes.

As with all the other methods of testing, radiography has its limitations. With normal industrial X-ray units, the limit of penetration into metals occurs at about the equivalent of four inches of steel, as Table I will show. The utilisation of expensive million-volt units extends the range to some six or eight inches, and a linear accelerator is being used in development work to penetrate some fifteen inches of steel. The use of energies up to the 20 million-volt range would enable much greater thicknesses of steel to be covered. However, for economical reasons, in industry radioactive isotopes are normally used to cope with steel of greater thicknesses than four inches.

TABLE I

SCOPE OF NORMAL INDUSTRIAL X-RAY UNITS

Kilovoltage range	Applications
30–60	Non-metals. Paper insulators, plastic assemblies, wood, paper, cast resins, etc.
60–120	Aluminium, magnesium and other light alloys up to 1 in. thick. Sheet steel and some steel-encased assemblies.
120–200	Light alloys 1 in.–3 in. thick. Steel ¼ in.–1 in. thick.
200–300	Steel up to 3 in. thick. Aluminium etc. up to 5 in.–6 in. Bronzes, gun-metals and the heavier non-ferrous alloys up to 2 in. thick.
300–400	Steel 3 in.–4 in. thick. Heavy non-ferrous alloys up to 3 in.
1,000	Steel from 4 in.–8 in. thick. Bronzes etc. up to 5 in.–6 in.

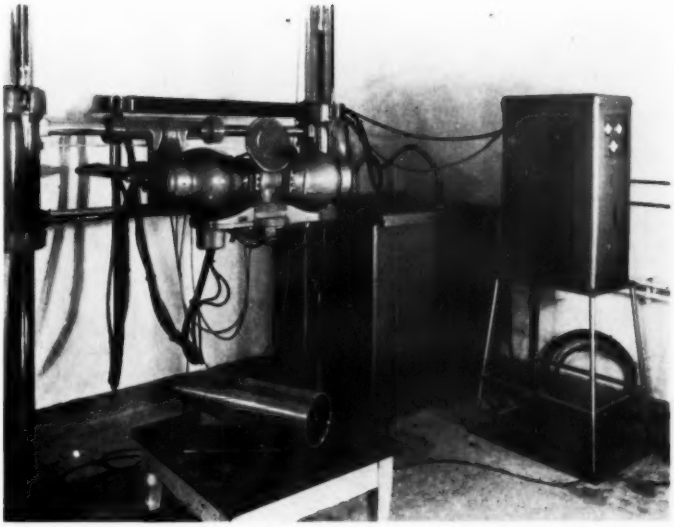


Fig. 1.—A typical industrial X-ray unit, capable of operating at voltages up to 250 kV

Radiography, also, is a costly process, both as regards initial outlay and daily operation, and a factor of great importance is the dangerous effect of X-rays, and gamma radiation from radioactive isotopes, upon the human body.

The radiographic examination of certain welds and castings is insisted upon by various government departments and insurance companies. Castings for aeronautical work, and welds in pressure vessels and nuclear power plant, are subject to a mandatory X-ray examination, and the process is also found invaluable for the examination of gas-filled or vacuum-tight fabrications, metallic or non-metallic sub-assemblies, and the training of employee welders or foundrymen.

Fig. 1 shows a typical industrial X-ray unit, capable of developing 250 kV across the tube and of penetrating some 3 in.-3½ in. of steel. There are, of course, many designs of such units, some of which are specially made for portability, or accessibility in confined areas.

X-ray examination lends itself particularly to use on materials other than metals. Radiography can be applied to an extremely wide range of materials, and any non-metallic substance, or any metal with a density less than that of lead, can be examined. Plastics, rubber and paper are perhaps three of the most common non-metallic materials which are regularly examined in the electrical engineering industry. Radiographic examination is the only method applicable to the investigation of assemblies, and the misalignment or absence of integral parts, or damage to internal components, can usually be readily seen.

At this point it may be advisable to explain briefly how X-rays reveal the internal condition of materials. During the passage of X-rays through any kind of matter they are to some extent absorbed, the degree of absorption depending, among other factors, upon the density and thickness of the material involved. During the examination of a specimen, voids within it will

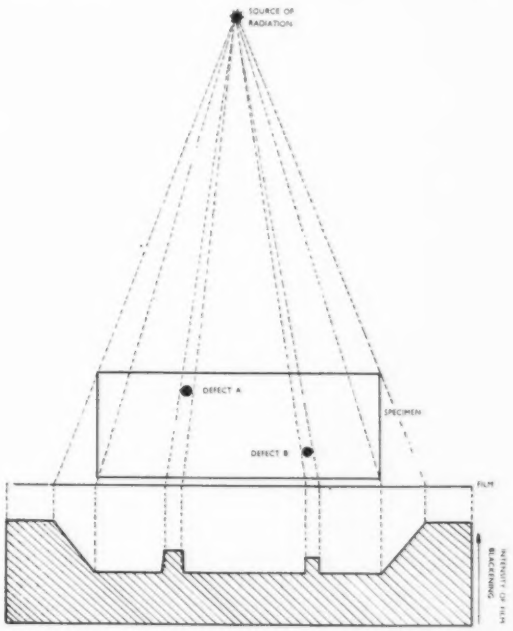


Fig. 2.—Diagrammatic representation of the effect of defects in steel upon the X-ray beam

absorb no radiation ; on the other hand, if some object of higher density, such as an inclusion of foreign metal, is contained within the material, then this will absorb more of the radiation. Since X-rays travel in straight lines, more rays will emerge from the specimen immediately below a void than elsewhere. Conversely, beneath a part of higher density, fewer X-rays will be present. This principle is shown diagrammatically in Fig. 2.

The image picked out by the beam of X-rays is usually recorded upon a special type of photographic film. The emulsion is blackened by the X-rays in proportion to the amount of radiation reaching it in a given time, and the lower part of Fig. 2 attempts to represent the degree of blackening.

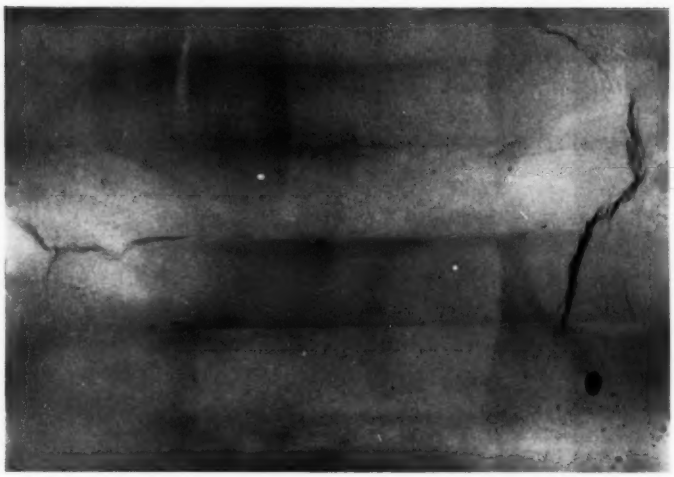


Fig. 3.—A radiograph of heavy cracking in a 2 in. thick phosphor-bronze casting

At each end of the film, where it is fully exposed to the radiation, the blackening is very intense, but near the edges of the specimen the film begins to be shielded, and so a decrease in blackening occurs until a level is reached at a point where the rays are penetrating the full thickness of the specimen. Both of the defects shown in Fig. 2 are in the nature of ' voids,' and as the proportion of rays arriving at the film below defect A is greater than elsewhere, a local intensification occurs. A similar effect is caused by defect B, but in this case the defect is smaller and the intensifying effect is less.

Generally, the following conditions are shown by a radiograph : (a) the presence of foreign inclusions of greater or less density than the parent substance, (b) the presence of several materials or components, as in the case of assemblies, (c) the absence or deformation of some component, (d) the presence of intentional or unintentional cavities. In the electrical engineering applications of radiography all these conditions are encountered.

The defects which are commonly revealed in welds or castings by X-rays are voids, shrinkage

Fig. 4. Radiograph of heavy porosity in a 1 in. thick weld

Fig. 5.—Radiograph of a darkroom clock, revealing a broken spring

defects caused during the solidifying of molten metal, slag inclusions resulting from poor cleaning processes during welding, lack of fusion, inclusions of foreign matter, and cracks.

Fig. 3 is a radiograph of cracks in a 2 in. thick phosphor-bronze casting, occurring during repair operations, and Fig. 4 shows porosity lying within a 1 in. thick weld. The radiography of assemblies may be fittingly illustrated by Fig. 5, a radiograph of a darkroom timer, which is self-explanatory.

No account of the radiographic method of non-destructive testing would be complete without some mention of the specialised techniques, one of which is stereo-radiography. This technique, as its name implies, is a method of obtaining a three-dimensional radiograph. When the pair of stereo films are viewed the specimen appears to be transparent, and any defect can be located in all three planes. This technique is particularly instructive in the case of assemblies.

Another useful adaptation of radiography is illustrated in Fig. 6. It is possible, by using special techniques, for an enlarged radiographic image to be obtained. In the study of fine detail, such as, for example, valve filaments, considerably more detail can thus be revealed.

High-speed radiography can be extremely useful for the study of quickly-moving processes. A short pulse of extremely penetrating radiation is directed into the specimen at short intervals, and, simultaneously, the radiographic image, appearing on a fluorescent screen, is photographed on cine-film. The rupturing of fuses, or the transfer of the welding bead, are examples of the utility of this technique.

Very frequently, fabricated or cast products requiring X-ray examination are too thick for

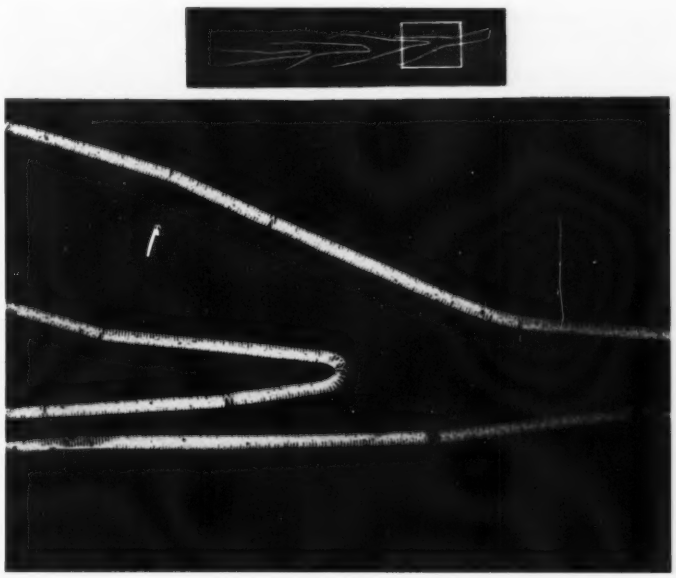


Fig. 6.—The ' enlarged radiograph ' technique. The section outlined in the top picture has been enlarged twelve times to provide the illustration below

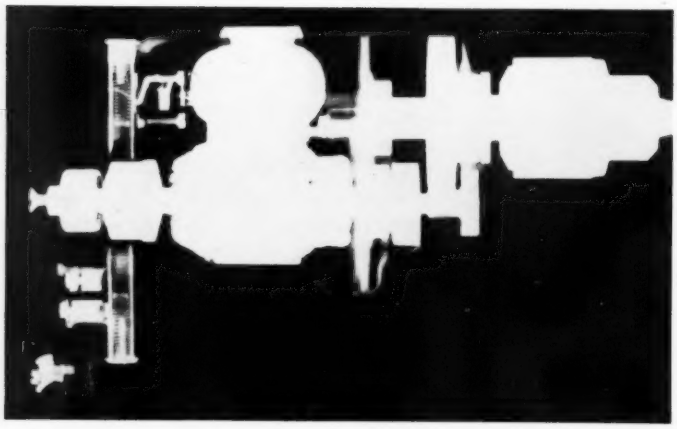


Fig. 7.—An electric pistol drill examined by X-rays

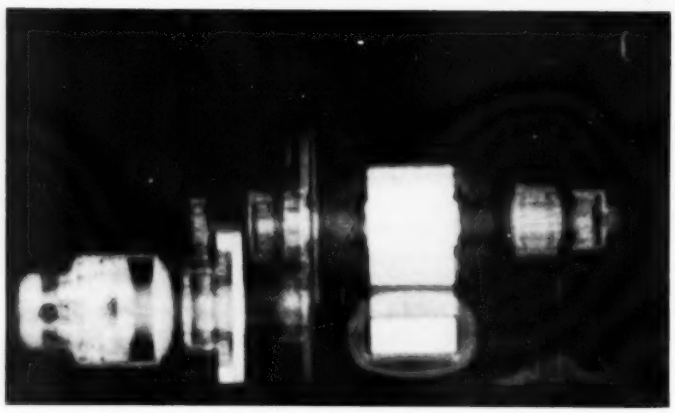


Fig. 8.—The same drill as in Fig. 7 taken with gamma-radiation from a cobalt isotope

penetration by the usual industrial X-ray unit, and here radioactive isotopes are brought into use. These isotopes, small cylindrical pellets of cobalt, iridium or caesium, are made radioactive in an atomic pile, when they emit extremely penetrating gamma rays, capable of penetrating some eight inches of steel. The exposure times required for satisfactory results are very long, when compared with X-ray exposures, although this is to some extent offset by the fact that gamma-ray exposures can take place, without attention, in shut-down periods. A comparison of results obtained by X-rays and gamma-rays is afforded by Figs. 7 and 8. It will be seen that, although more detail is revealed in the thicker sections, there is, generally, less contrast and poorer definition in Fig. 8. A gamma-ray picture of shrinkage defects in a 5 in. thick leaded gun-metal casting is shown in Fig. 9.

Ultrasonic Flaw Detection

Most of the disadvantages inherent in the X-ray method of examination do not apply in the case of ultrasonic flaw detection. Ultrasonic methods are far more easily and quickly applied, and are much less expensive. Penetration of steel to a depth of fifteen feet can be achieved, and although there is some slight reduction in sensitivity as the thickness increases, the test is extremely critical and can sometimes pick up minute changes in metallurgical conditions. Another most important advantage is that, unlike X- and gamma-rays, the ultrasonic waves have no inimical effect upon health, and therefore the test can be applied in an open workshop without the need for roping off danger areas or stopping production.

On the other hand, ultrasonic testing cannot be applied to as wide a range of materials as can radiography, and as no picture of the conditions obtaining in the interior of the object is commonly available, interpretation can be difficult. The nature of any flaw must be deduced from a line trace on a cathode ray tube. The operators must be skilled men.

This method of inspection may also be seriously complicated, or even rendered impossible, by coarse structure in the material, due of course to the extremely sensitive nature of the test.

In principle, ultrasonic testing is accomplished by the introduction into the specimen of vibrations

Fig. 9.—Shrinkage defects revealed in a 5 in. thick leaded gun-metal casting, by gamma-radiation

with a frequency of one to six megacycles per second. The ultrasonic waves will travel with very little attenuation for considerable distances in homogeneous materials, and are reflected either by the far boundary of the specimen or by an internal flaw. This principle is illustrated, together with a block diagram of an ultrasonic circuit, in Fig. 10.

The ultrasonic waves are produced by means of the piezo-electric effect of certain crystals, which converts electrical impulses into a mechanical vibration. A coupling medium, such as oil, is required to ensure the transmission of the impulses from the surface probe into the specimen. On their return to the surface, after reflection, the waves are picked up by either the transmitting crystal or a separate one, and are reconverted into electrical impulses, which appear on the trace of the cathode-ray screen.

A sketch of an ideal ultrasonic trace pattern is given in Fig. 11. When the pulse is transmitted into the specimen an 'initial peak' appears at the left of the trace, as shown in position (a). A time-base system causes the electron beam of the cathode-ray tube to sweep across the screen, and when the waves reflected by the far boundary of the specimen return to the crystal, their arrival is indicated by another peak, displaced to the right, as shown in Fig. 11(b). The instrument can be calibrated so that the distance between the two peaks relates to the thickness of metal traversed by the beam.

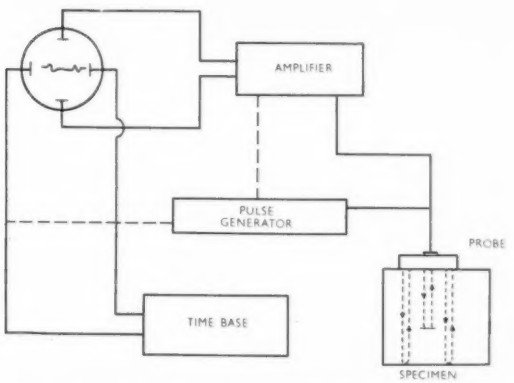


Fig. 10.—A block diagram of an ultrasonic flaw detection unit

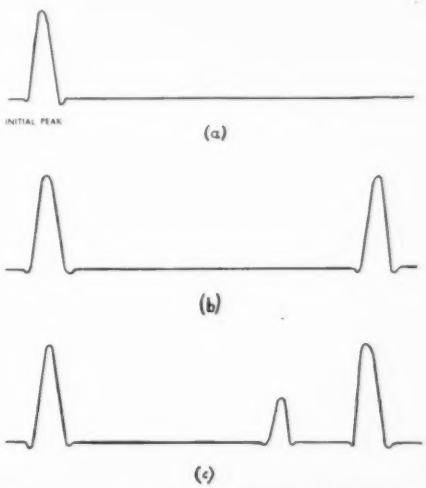


Fig. 11.—The ideal ultrasonic trace pattern

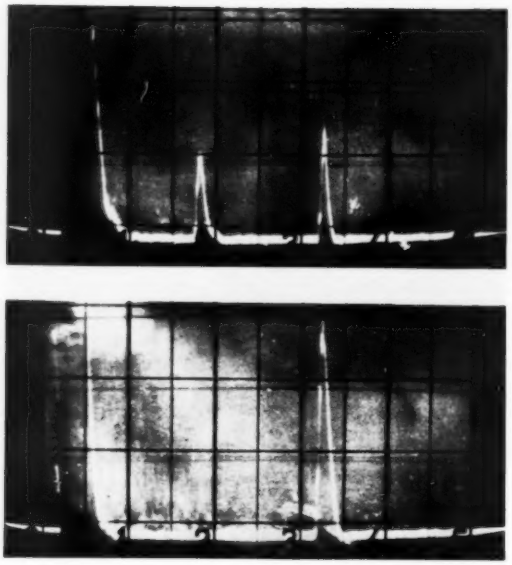


Fig. 12.—*The ultrasonic traces obtained on* (*above*) *defective and* (*below*) *sound material*

Should a part of the ultrasonic beam be reflected by an internal flaw, it will of course arrive early at the probe, and a third peak will appear on the screen as in Fig. 11(c). The exact position of this fault echo on the trace will be dependent upon the depth of the flaw below the surface, and the accurate location of the defect can therefore be calculated from the relative position of the fault echo. The amplitude of the peak will roughly indicate the size of the discontinuity. In extreme cases the base echo deflection will become attenuated, and if the defect is large enough to absorb all the transmitted energy, the deflection to the right of the trace will disappear completely.

Coarse structure, or general fine porosity within the specimen, may cause blurring along the whole of the trace, and poor contact between the crystal and the specimen may completely alter the characteristics of the trace. Two indications obtained in routine practice are shown in Fig. 12, the top trace being from defective material, and the bottom indication from a sound product.

Crystals of varying frequency can be used to alter the sensitivity of the test. General practice is to use frequencies of between one and six Mc/sec because it is found that with higher frequencies the test can become much too sensitive, and unimportant characteristics of the material can be shown as possible defects. There are, of course, various ultrasonic flaw detection techniques, selected according to the specimen and the requirements of the examination. For example, the waves may be directed into the specimen at a predetermined angle instead of at 90° to the surface, or two crystals may be used on diametrically opposite sides of the object, in which case no reflection occurs, the transmitted waves being picked up at the far boundary of the specimen.

It is fortunate that the ultrasonic method of inspection comes into its own in those cases where radiography is likely to prove of no avail. Defects lying parallel to the surface are readily picked up by ultrasonic waves but not by X-rays ; cracks normal to the surface can be detected with X-rays, but not by ultrasonics.

One of the major applications of the ultrasonic method of testing is the examination of large forgings, such as rotor shafts, which are examined both radially and axially. Rotor end-bells also lend themselves to this method of inspection, as do a wide variety of brazed and soldered joints. When literally hundreds of such joints have to be inspected, a point is scored by the ultrasonic method, for a radiographic examination would be very costly, and slow in comparison. The adhesion between tinned or white-metalled bearing surfaces and the base metal is a very important application.

Welded seams can also be inspected, and in this connection the ultrasonic and radiographic methods of inspection may be complementary. For example, when a welded seam has to be radiographed in its entirety to satisfy an insurance company, it is an economical advantage to test first by ultrasonic methods, so that the majority of any defects may be repaired before the more expensive X-ray examination is applied. Also, if a defect shown in a radiograph is serious enough to warrant its removal, its precise depth below the surface can be ascertained by ultrasonic waves ; an obvious advantage where thick welds are concerned.

Magnetic Crack Detection

Radiography and ultrasonic testing are the only two methods which can be relied upon to locate

defects lying some distance below the surface of the specimen. Magnetic crack detection will sometimes reveal sub-surface flaws, but usually only if these defects are immediately below the surface, or if they are very large.

Nevertheless, magnetic crack detection does find a wide application in the examination of such components as turbine blades and discs, forging blanks, studs, bolts and pinions, tools and similar articles. It can, of course, be of use only in the case of ferromagnetic parts, when it will reveal cracks, non-magnetic inclusions, or other discontinuities on, or immediately below, the surface.

The underlying principle of magnetic crack detection is simple, relying upon the disruption of magnetic lines of force by surface discontinuities. The resultant strong magnetic field in the air above the defect is used to attract finely divided magnetic particles. A local concentration of the particles indicates, with a fairly high sensitivity, the presence and the extent of a flaw. Defects lying immediately below the surface are shown by more blurred indications.

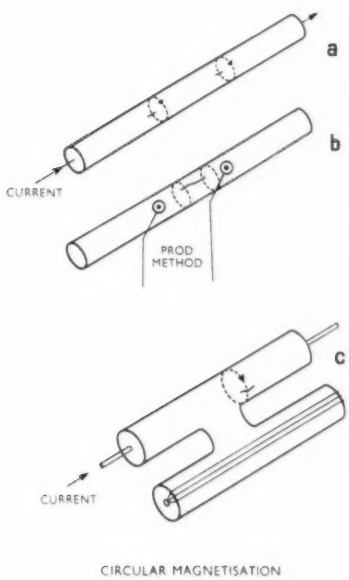


Fig. 13.—*Methods of achieving a circumferential flux for magnetic crack detection*

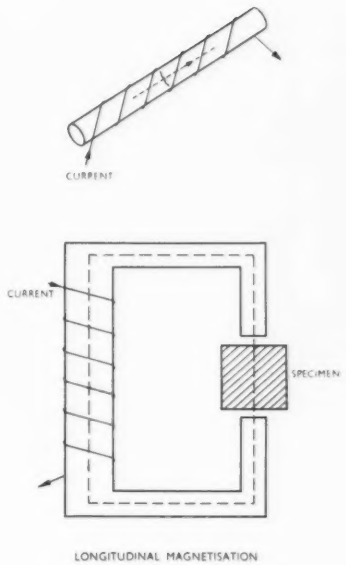


Fig. 14.—*Typical procedures for obtaining a longitudinal flux*

Magnetisation of the part may be achieved by one of several methods. For maximum sensitivity the direction of the magnetic flux should be at right angles to the principal plane of the defect, and so, for the detection of cracks lying in a longitudinal direction, a circumferential flux must be induced. Three methods of achieving this are shown in Fig. 13. With a solid specimen (a) it is necessary merely to make contact at the ends, or, as shown in the prod method (b), by two small movable contacts. With hollow parts a conductor bar may be inserted through the centre of the bore (c), or coils of wire may be threaded around the component.

Cracks tending to travel in a circumferential direction require a longitudinal magnetic flux for optimum sensitivity, and two typical procedures are shown in Fig. 14. The upper diagram again refers to a solid bar, this time with turns of wire around it. In the lower diagram the specimen has been placed between the poles of an electromagnet.

Either direct or alternating current may be used for magnetisation. With a.c., a skin effect is produced, and the magnetic flux achieves no real

depth of penetration. However, a.c. has the advantages that heavy currents are readily obtainable from the mains via a step-down transformer, and demagnetisation after examination is a simple matter. Direct-current magnetisation has an effect throughout the specimen, except at sharp changes of section, and with it even comparatively deep-seated defects may be indicated. The supply source, however, can be complicated, and there are also voltage-control difficulties.

Three methods of testing are commonly used. In the ' current flow ' method, magnetic indicating ink, composed of fine ferrous particles in a fluid such as paraffin, is applied while the current is passing through the component. This is the most sensitive of all the known techniques, but it introduces the danger of overheating the part, particularly when small components are being examined. It is nevertheless a most popular method, and is especially superior when flaw depth has to be determined, or for the detection of flaws in awkward parts of the specimen.

The magnetic ink may alternatively be applied after the current has been switched off, this technique depending upon the residual magnetism within the part to reveal any defects which may exist. When the material under test has a high magnetic retentivity the method is successful, but if a.c. is used demagnetisation can occur before the indicator is applied as a result of the current impulse ceasing at the wrong part of the a.c. cycle.

Flash magnetisation is a variation of this procedure. A large current of about 1,200 to 1,500 amperes is passed through the part for one or two seconds only, and the magnetic ink applied immediately after switching off. Burning can be prevented by the use of copper gauze pads between the contacts and the part.

There are many types of magnetic crack detector available, some of which have a wider scope than others. Permanent magnets can, of course, be used to magnetise the test object, but most of the instruments make use of an electrical current. Most equipment relies upon transformers, or even motor-generators, for the establishment of the magnetic flux. Current variations are obtained by a Variac auto-transformer, and the current flow is indicated by an ammeter. Pumps are sometimes fitted to braw the magnetic ink from a drainage well and eject it over the part, and electrically driven agitators prevent sedimentation of the magnetic particles.

The field strength has to be adjusted for maximum sensitivity at the beginning of each examination, the limit of sensitivity being reached when particles begin to be attracted to sound parts of the specimen. If a full test is to be made, the examination of each area must be carried out with the flux running in both the longitudinal and the circumferential directions, and some detectors are equipped to provide both types of magnetisation successively.

It is not always possible to photograph indications because of lack of contrast between the defect and the background. Prior application of a zinc-oxide wash will increase the contrast, but otherwise the indication may be transferred to transparent adhesive tape.

Any magnetism remaining in the part after completion of the test must usually be removed, as it may otherwise become an inconvenience in later stages of manufacture. With alternating current, demagnetisation is accomplished by removing the part slowly from the magnetic field. Direct-current demagnetisation is not so quick, and involves the subjection of the part to repeated reversals of current which, at the same time, is progressively reduced. Any residual magnetism will be automatically removed if the part is later subjected to heat treatment.

Another method of testing for cracks or similar defects makes use of a meter or a neon lamp as a flaw indicator. This procedure is faster than the usual method, and is more suitable for work on production lines. Direct current is used, and the surface of the part is scanned with a movable coil. The presence of a defect will set up an e.m.f. in the coil. This e.m.f. is amplified and made to operate the indicator, or alternatively a mechanism for the segregation of faulty parts.

Differences in potential between two points may also be used to indicate cracked material, as the presence of a crack, by increasing the length of the path, will increase the natural potential difference between the points. This method has an application in the examination of welds, and it has been found that, with the points of the probe astride the weld, minute cracks 1/16 in. deep may be detected.

Fig. 15.—An example of magnetic crack detection. The same specimen before and after test, using fluorescent ink

Photograph reproduced by courtesy of Magnaflux Corporation

A striking example of the efficacy of magnetic crack detection is afforded by Fig. 15, showing the same article before and after test. In this illustration, the usual indicating ink has been replaced by one in which the particles have been rendered fluorescent. This greatly increases the sensitivity of the examination, since even minute flaws attract attention.

Magnetic Sorting Methods

Departing for the moment from the consideration of quality control, magnetic methods of testing can be used to great advantage for the sorting of mixed materials, such as bar stock.

Sorting methods are usually based upon the comparison of the magnetic characteristics of two physically similar specimens, which are used as the cores of two transformers, or inductances. One of the specimens is known to be sound, and of an acceptable nature, and is used as a standard.

The circuit is very similar to that of an inductance bridge. With the standard in one coil, and the piece to be tested in the other, sorting is determined according to the state of balance of the bridge. Indications are usually obtained on a cathode-ray screen, and a family of traces actually obtained appears in Fig. 16.

The curves obtained on five different steels are reproduced in Fig. 16(a), and the ease of sorting in such a case as this will be readily apparent. The effect of differences in the carbon content of steel is indicated by the traces in (b), whilst the variation in (c) is caused by a difference of only 0.5% in the molybdenum content of steel. The traces shown in (d) were obtained during the measurement of the depth of case-hardening in a series of specimens.

In the field of electrical engineering, these testing methods can find utility in the examination of ingots, billets, sheets, rods, tubing, castings, forgings and busbars.

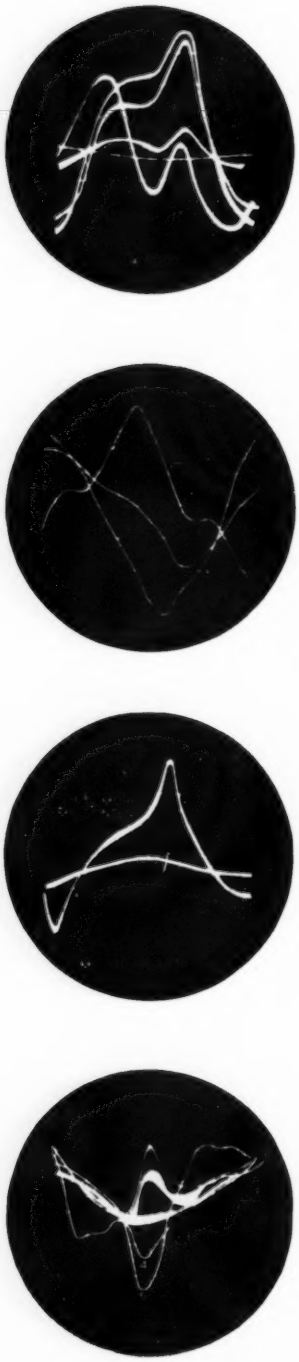
Conductivity Measurements

The actual conductivity of metal in its own right can, of course, be very important in electrical engineering, and an instrument capable of measuring the conductivity with an accuracy of $\pm$ 1.5% is available. The minimum thickness for testing on this instrument is of the order of 2 mm, and, for absolute readings, a flat surface of about one square centimetre on the specimen is required.

The instrument utilises eddy currents set up within the specimen, the currents being induced by a probe carrying a detecting coil which is connected to a bridge circuit. The impedance of the detecting coil is affected by the eddy currents in proportion to the conductivity of the material, and the instrument is so designed that direct readings of conductivity can be obtained on a large dial. The probe can be used on surfaces which are moderately rough, or coated with paint, and the equipment can be used on graphite, copper, bearing metals, nickel silver, resistance alloys and austenitic steel.

Thickness Measurement

Magnetic methods are also used for the measurement of the thickness of non-magnetic coatings



upon a magnetic base. The base material is used as one limb of the core of a transformer, the thickness of material being measured forming the equivalent of an air gap in the core. With increase of thickness of the non-magnetic material the coupling between the primary and secondary of the transformer falls, and the e.m.f. induced in the secondary therefore decreases with increasing thickness. The transformer is built into a scanning probe, and an alternating current having a steady r.m.s. value is passed through the primary circuit. Indications are usually read off on a dial. The convenience of this test for the thickness determination of paint films on steel, tin-zinc or zinc or cadium plating, or Insuline coating on transformer laminations, will be readily appreciated.

The bridge circuit may be used for the measurement of plate thickness. Two identical electromagnets are used, one of which is placed on a standard test piece, and the other in contact with the plate under test. A low a.c. voltage is applied to the bridge, and reactance differences between the magnet windings cause an out-of-balance current to flow through the indicator. An accuracy of about ·005 in. on steel up to a quarter-inch in thickness can be obtained.

Ultrasonic methods may also be used for the determination of plate thickness, testing from one side only. This is especially valuable in the case of boilers and similar products in which only one surface is readily accessible.

If a generator of mechanical vibrations (such as the crystal and electrode system previously described) is attached to a plate, the plate can be made to vibrate. If the frequency of the generated mechanical waves is continually changed, their wavelength will also change, and whenever the plate thickness is an integral multiple of the

Fig. 16.–*Some traces obtained on a sorting instrument*

(a) *The traces from five different steels.*
(b) *The effect of differences in carbon content of steel.*
(c) *Trace differences due to a variation of* 0.5% *in molybdenum content of steel.*
(d) *The depth of case-hardening on a series of specimens.*

wavelength, an abrupt increase occurs in the amplitude of the mechanical vibration. If the plate is being made to vibrate by an ultrasonic generator this onset of resonance in the plate will cause an increase in absorption of ultrasonic power from the generator, since the plate and the generator are coupled together. This increase can be detected electrically, and the frequency of the ultrasonic generator at which the increase occurs can be determined. From a knowledge of this frequency the plate thickness can be deduced.

Several of the manufacturers of ultrasonic flaw detection equipment have made modifications enabling wall-thickness tests to be carried out on the normal equipment. In some cases, special wall-thickness meters can be clamped on to the equipment and, when resonance is obtained as revealed by the trace on the cathode-ray screen, the plate thickness may be read off directly from the meter.

Leak Detection

The detection of minute leaks is often of the first importance, especially in the case of vacuum-tight products and nuclear power components. Considerable attention has been paid in recent years to the development of sufficiently sensitive detection methods. One such process utilises radioactive gas, the escape of which is measured by means of a scintillation counter. This test can be extremely sensitive, but in common with all processes involving radioactive materials it suffers from the possibility of health hazards.

One leak detector in principle is designed to be extremely sensitive to a particular gas in the presence of normal atmospheric gases. Nitrous oxide is usually chosen as the detector gas, since it is not hazardous and is not found in nature. The vessel to be tested is pressurised with the test gas, and the surrounding air outside the vessel is sampled. By using an infra-red gas analyser, a sensitivity of one or two parts per million can be obtained, and with refinements such as collecting the escape gas for several hours before analysing, leaks at least down to 10^{-2} lusecs (micron-litres/sec) can be measured. A good feature of this instrument is that it fails to safety ; it never ignores a leak, but may on occasion appear to indicate such a defect when it does not exist.

The infra-red gas analyser works on a bridge principle. A sensitive bridge-connected double element condenser-microphone has a compartment on each side of the diaphragm filled with the test gas. An infra-red beam, intensity-modulated at 7 cycles per second, is split and passed through a standard air sample on the one hand and through the sample under test on the other. After its journey through the test columns the beam enters the microphone, one part on each side of the diaphragm. The test gas molecules are excited by the infra-red rays, and impinge on the microphone at 7 cycles per second. As long as there is no test gas in the sample column, the diaphragm of the microphone is excited equally from both sides, and therefore does not move. If test gas should be present, it will absorb part of the energy in the beam, at the specific wavelength that excites the gas molecules in the microphone. The two sides of the diaphragm will then be unequally bombarded, and the diaphragm will move at the same frequency—7 cycles/sec. The output of the microphone is then amplified and indicated on a calibrated meter.

The gas detection is very specific, as the action of the instrument is dependent upon the frequency of internal vibration of the gas molecule. However, large concentrations of gases of similar molecular construction and weight can cause a partial response. For example, N_2O and CO_2 are fairly close together in response frequency, and several per cent. of CO_2 gives an indication similar to several parts per million of N_2O.

Another gas detector, similar in application to the infra-red detector, and even more sensitive, is the palladium barrier hydrogen detector. This instrument is based on the phenomenon that hydrogen gas diffuses through heated palladium, and can thus be separated from all other gases.

The vessel under test is evacuated, and surrounded by a hydrogen atmosphere. The gases diffusing into the vessel are passed through a liquid air trap to freeze out materials which would ' poison ' the palladium barrier, and are then passed over the barrier. The hydrogen diffusing through the palladium is measured on a sensitive ionisation gauge.

The vacuum system has to be kept free from oxygen, as this gas combines catalytically with

hydrogen in the presence of palladium, thus reducing the sensitivity of the test. A sensitivity of 10^{-4} lusecs is readily achieved.

Leaks in vessels can also, in some circumstances, be found by measuring the electrical breakdown strength of a vacuum in the vessel, such measurements being repeated over a period of time.

The mass spectrometer finds wide application for leak-testing vacuum systems. The vacuum vessel is surrounded by the test gas, and the vacuum inside the vessel is sampled. Any gases present are ionised, electrically accelerated, and deflected electrically or magnetically. Atoms of a specific mass are deflected through a definite angle, and atoms having the atomic mass of the test gas can therefore be separated from all others. The method of collection and measurement of these atoms varies, but modern instruments all include a direct-reading meter which continually monitors the vacuum. Sensitivities of 10^{-5} lusecs can be achieved on some models.

Other Testing Methods

One of the most widely known methods of non-destructive testing, although perhaps not usually associated with this group, is the test of sulphur printing, used to reveal the distribution of segregated sulphides in steels.

The sulphides, when attacked by a dilute acid, evolve hydrogen sulphide gas, which has the property of staining photographic bromide paper, and in this way clear permanent indications of the location and extent of the sulphides are obtained.

A wide range of testing procedures for defects in non-magnetic materials, and non-metals, has been evolved. One of these techniques, the dye-penetrant process, has a particular application when metals with no magnetic properties are concerned. The process, however, will only reveal defects which are open to the surface, but will show these even though they may be too small for visual detection.

The part to be inspected is thoroughly degreased, and is sprayed with a red dye of very low surface-tension, which penetrates into even very tight cracks. After allowing a certain time for penetration to occur, the surplus dye is washed off with a solvent, and a white absorbent coating applied. The dye remaining in the defects is absorbed by this coating, and in this way the defects are revealed.

In addition to locating flaws, a rough indication of the depth can be obtained from the amount of dye extracted. Deep flaws tend to form a blurred red patch, rather than a fine line or spot. Perhaps the most serious limitation of this test is that oily or painted components do not lend themselves easily to examination, since even if the oil or paint on the surface is removed, sufficient may remain in the defects to prevent access of the dye.

The dye-penetrant test can also be applied to non-metals, and the red dye may sometimes be replaced with advantage by a fluorescent indicator.

An electrostatic process has also been developed for the examination of non-conducting material such as glass, porcelain or ceramics, for surface flaws. A highly penetrating and electrically conducting proprietary solution is first applied, and then the surplus removed, so that any cracks that may be present remain as elec-

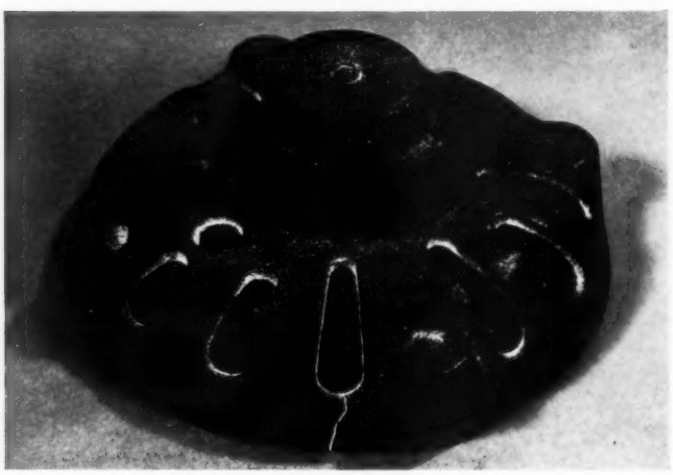


Fig. 17.—The dye-penetrant method of testing

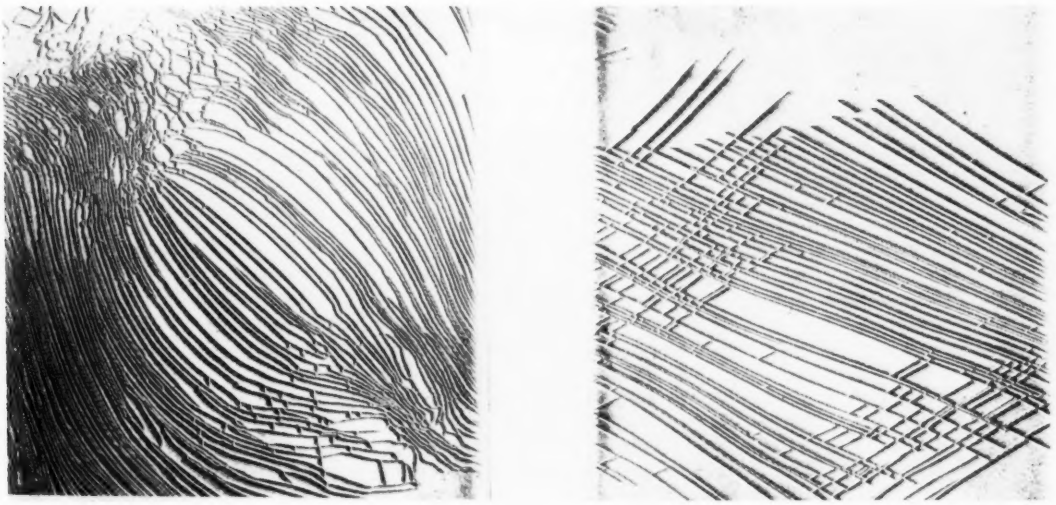


Fig. 18.—Surface flaws found on enamelled specimens by means of the electrostatic powder test

trical conducting paths in an otherwise insulating surface. Electrified particles are blown on to this surface, when they collect around the cracks, but not elsewhere.

These two processes, the dye-penetrant and the electrostatic procedure, are illustrated in Figs. 17 and 18 respectively. It will be apparent that any defects are revealed with extreme clarity.

The brittle lacquer method of stress measurement is well-known, but improvements in the process have now made the test more simple, and more conclusive. The lacquer—again a proprietary production—is painted on to the part and allowed to dry. The specimen is loaded, either by actual operation or by laboratory simulation, and the resultant cracks in the lacquer will reveal, in similar fashion to the contours of a map, the varying pattern of the stresses involved.

Future Developments

Very few of the methods of testing discussed in this article have yet been fully developed, and work is constantly being undertaken either to avoid one or other of the existing limitations or to cope with new, more stringent, demands necessitated by the general trend towards higher quality. In the radiographic field, for example, several new processes are being evolved.

It has been possible for a long time to reveal a radiographic image on a fluorescent screen, in place of film. These screens were encountered, some years ago, in the ' pedascopes ' used in footwear shops. Two of the disadvantages in the early type of screen, as far as non-destructive testing procedures were concerned, were its lack of definition and the general dullness of the image, necessitating some kind of viewing hood or a darkened room for interpretation purposes.

Both of these drawbacks have now been eliminated by the development of the image amplifier, one model of which is taken as an example. Briefly this instrument consists of a fine-grained fluorescent screen, backed by a photo-sensitive electron-emitting surface, which forms one end of an image-orthicon tube. The electrons emitted from the screen backing are accelerated towards the other end of the tube by a potential of about 25 kV and are focussed to form an image on a second fluorescent screen.

This screen has a diameter of only about one inch, and produces an image of greatly increased brightness and definition. The secondary image is viewed by an optical system of lenses and mirrors, and no dark room is necessary.

The image intensifier has proved its value on industrial materials at kilovoltages up to about

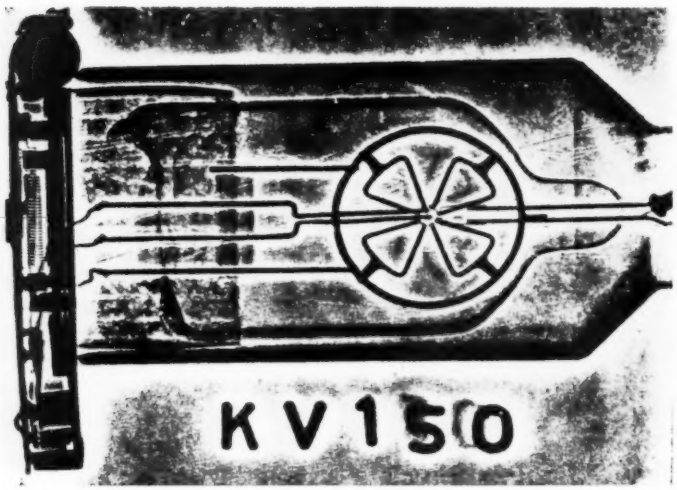


Fig. 19.—A typical xeroradiographic image

120—a range which is useful for the radiography of sheet steel, plastics, rubber and paper, thin sections of light alloys, and some welds, and it is to be hoped that future developments may extend its use up to 300 kV.

It will be readily appreciated that this technique greatly reduces the cost, and the time, of X-ray examination. For a large number of investigations permanent records may not be essential ; even if they are, the image shown by the amplifier can be photographed on cine-film.

A second non-film radiographic technique is known as 'xeroradiography,' and, as its name implies, is a development of the well-known xerographic process.

This technique was pioneered in the United States of America and is achieving exceptional results in that country. The X-ray film is replaced by a selenium-coated plate, and it is, apparently, due to the difficulty of obtaining a satisfactory selenium coating that the process has not yet developed into a commonly used technique.

The plate is charged by passing it beneath a wire carrying some 6,000 to 12,000 volts. During exposure to X-rays, the selenium is discharged in proportion to the amount of rays reaching its surface, and a latent radiographic image is thereby formed upon it. Dusting the exposed plate with a powder, the particles of which are attracted to the charges remaining on the plate, renders the image visible. A typical xeroradiographic result appears in Fig. 19.

The sensitivity of fault detection obtained by this technique appears to be even better than when the usual film is used, and a further advantage lies in the fact that the plate can be used for hundreds of exposures, by discharging and recharging it. A permanent record of the image can be readily obtained on ordinary paper by fusing the particles of powder, which are resin-based, into its surface.

At the present time, more development work is being undertaken in the field of ultrasonic testing than in any other. Ultrasonic testing, a development from the war-time radar, is rapidly 'growing up', and the full capabilities of the method are certainly not yet realised. If, at the moment, more limitations appear to exist with this method of testing than with any other, it is because time has not allowed the investigations necessary for elimination.

Experiments in which the specimen is immersed in water, with the ultrasonic probe suspended above it, also below the water level, have largely obviated the problems that arise in normal techniques when the object under test is of complex shape. Since the probe in this case in not in direct contact with the specimen, crystal wear is greatly reduced, and rough surfaces present no problem. The inspection process can be made largely automatic.

A serious attempt is being made, with some success, to present the ultrasonic findings in a plan view, similar to a radiographic film. The defects are shown as bright spots in an otherwise dark background, and are represented in their correct location. Although with this method the depth of the flaw below the surface is not immediately apparent, the presentation is obviously preferable to the single line scan of the present instruments.

The development of variously designed probes is helping to provide even more accurate location of defects, and to prevent ill-defined images due to secondary wave formation. Detector units are becoming more portable, and it is fair to say that every present limitation is receiving considerable attention.

Conclusion

Non-destructive testing is a comparatively young, and vigorous, science. New, and more difficult, problems arising from complexities of design and quality requirements are evolving new methods of testing, and as long as there are problems to solve the work will remain interesting and challenging.

The day may eventually dawn when the non-destructive testing engineer, emulating the television producer, will sit at his desk and watch the results of his quest for quality control appear in three-dimensional view on a screen before him, but until that time arrives inspection will continue on the shop floor, and development work will be carried out in the laboratory, to ensure that the standard of goods produced remains at a high level.

Electric Drives for Corrugated Board Production

By P. W. R. GATLIFF, B.Sc., A.M.I.E.E., Chief Machine Control Engineer.

CORRUGATED BOARD has been finding increasingly wide application for the manufacture of boxes and as packing material generally. It is strong, flexible, light in weight and easily stored. The rising demand for it has promoted the installation of new machinery and the search for more efficient drives, enabling consistently high quality production to be achieved. The tonnage of packaging board made in Britain has increased by about 70% since the end of the war.

A new corrugating machine has recently been installed at the Glasgow works of the Andrew Ritchie division of Bowater-Eburite Fibre Containers Limited. This machine, made by Masson Scott and Co. Ltd, under licence from the Samuel M. Langston Company, Camden, U.S.A., with electric drives by The English Electric Company, can make corrugated board 85 inches wide at 650 ft/min. Direct-current motors were chosen for the drives of the various sections, supplied from motor-generator sets to give ease of speed control over a wide range, and close speed-matching between sections. Two special problems had to be solved : the provision of a ' tapered speed ' control for the glue-roll drive, and variable speed drives for the take-off conveyors, having a speed range of nearly 100 : 1. This article describes the machine, the drive arrangement and the controls for the two special drives.

Single Facer and Double Facer

Double-backed corrugated board is made in the machine in two stages. The first stage is carried out in a ' single facer ' which corrugates the paper, applies glue to the tips of the corrugations on one side, and then sticks on a flat sheet of paper to form a ' single faced ' board. This process is shown diagrammatically in Fig. 1. The main rolls are geared together and driven by a 50 h.p. motor. Other motors drive the pre-conditioner (3 h.p.), adhesive rolls (2·6 h.p.), bridge conveyor (5 h.p.) and long conveyor (5 h.p.). All these are separately excited motors, connected in parallel to a common generator and designed with the same inherent speed regulation so that their speeds remain in step throughout the load range. The overall speed of the machine is varied by field control of the generator. Individual field rheostats are provided for speed trimming of the drives. A separate d.c. supply is switched on to the adhesive roll motor when the machine speed is below 150 ft/min, to

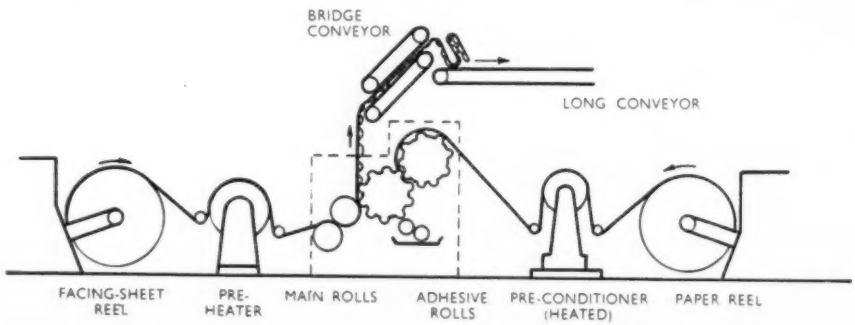


Fig. 1.—Diagram of single-facer end of machine

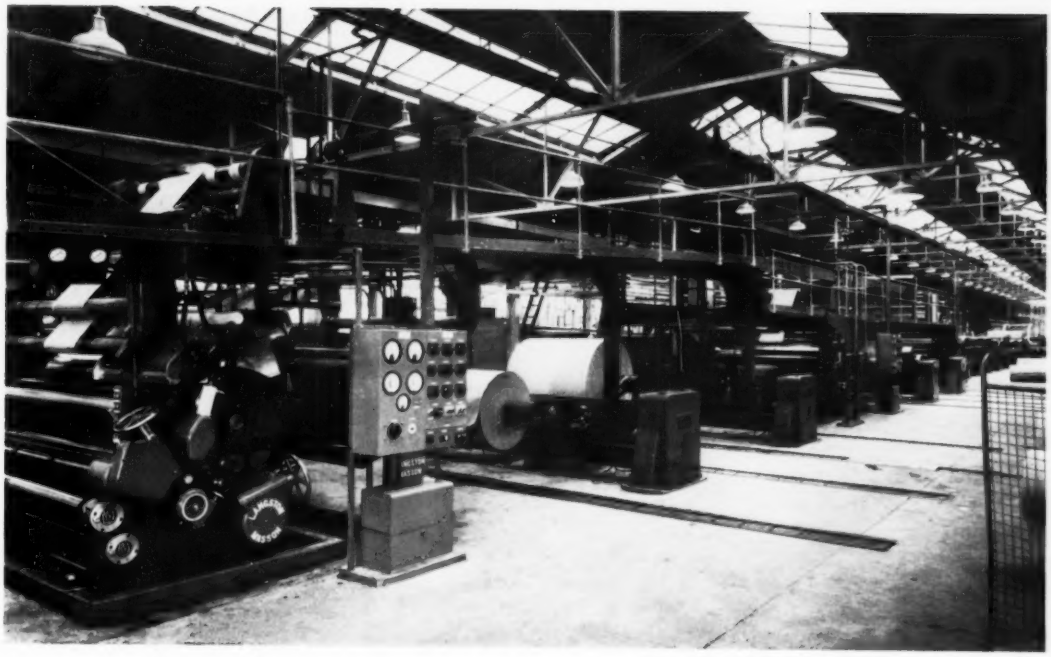


Fig. 2.—Corrugator from single-facer end

keep the adhesive rolls turning and thus prevent the glue from drying on them.

Fig. 2 shows the machine from the single-facer end but with no paper passing through it.

The second stage of manufacture is carried out in the ' double facer ', which takes the corrugated board from the ' single facer ', applies glue to the free tips of the corrugations, and sticks a second sheet of paper to it, thus forming two sheets of flat paper glued to either side of the corrugated paper. The glue is then dried on a drying table and the completed board scored for bending and slit and cut into the desired shapes for the packing boxes. Stacking and delivery tables feed the board away from the machine.

Fig. 3 shows in outline the parts of the double facer. A 100 h.p. motor drives through shafting all the various parts of this end of the machine except the glue rolls and delivery tables. The main motor is fed from its own d.c. generator, speed being controlled by field control of the generator.

Fig. 4 is a view of the slitter and scorer unit at the end of the drying table.

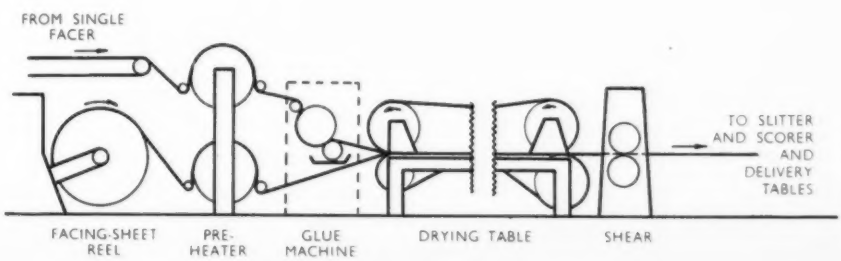


Fig. 3.—Diagram of double-facer end of machine

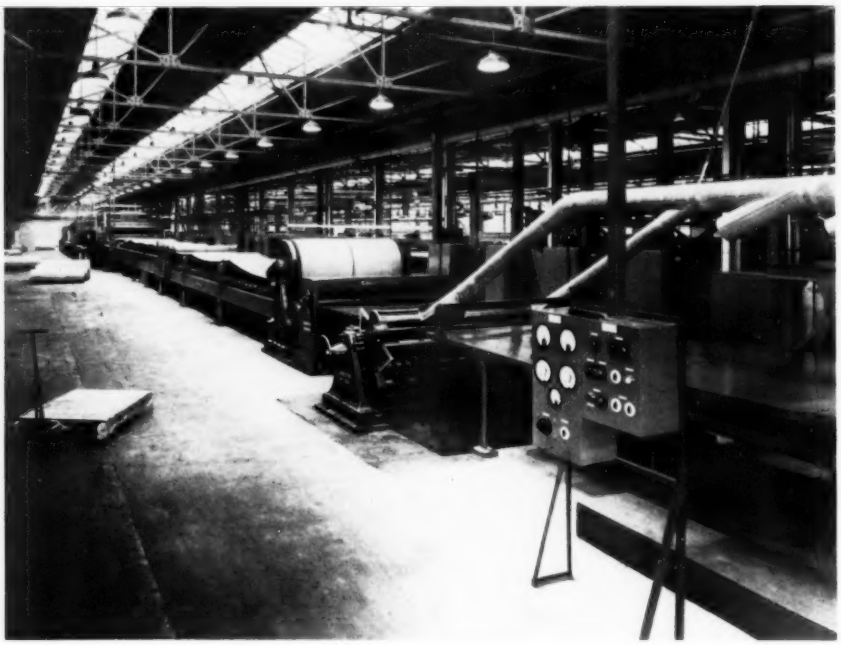


Fig. 4. Corrugator from delivery end

Glue Roll Drive

The amount of glue which is transferred from the glue roll to the corrugated paper depends on their relative surface speeds ; the greater the ratio of roll speed to paper speed, the more glue is transferred. It has been found that in order to obtain consistent quality of corrugated board over a range of machine speeds it is necessary to vary this speed ratio. At low operating speeds sufficient adhesive must be transferred to compensate for the longer heating time in the dryer section. At higher speeds, glue penetration is less, and so is the heating and curing time, so that less adhesive is required. The result is that the glue roll speed must be ' tapered ' in relation to the paper speed, and a typical speed relationship is shown in Fig. 5.

The glue-roll motor armature is connected in parallel with the double-facer drive motor to the double-facer generator so that the speeds of the two motors would normally be matched. In order to produce the tapered difference, a booster generator is connected in series with the glue roll motor. The field of this generator is in two parts, one fixed and the other variable, the latter controlled from a magnetic amplifier. The fixed field determines the speed off-set at low speed, and the variable field produces the taper. The magnetic amplifier is controlled from a circuit which com-

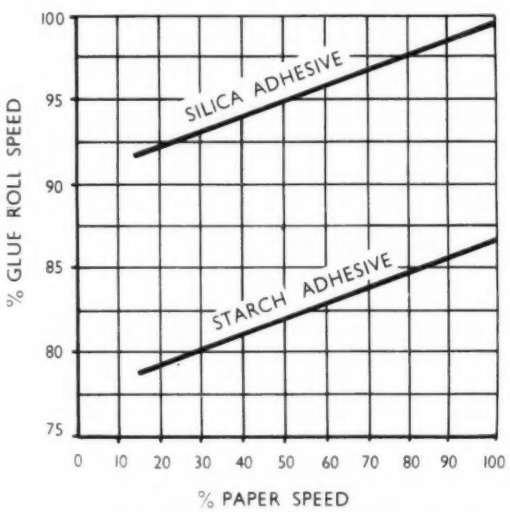


Fig. 5.—Typical glue-roll speed requirements

pares the double-facer motor voltage and the glue-roll motor speed as measured by a tachometer. The field of the glue-roll tachometer is adjustable and thus gives adjustable taper control.

Sheet Delivery Tables

After the board leaves the double-facer section it passes through a rotary shear, then through slitter-scorers which score the board for subsequent folding and slit it longitudinally, and then through a duplex cut-off which cuts it into sheets. The individual sheets have to be stacked, and this is done automatically by allowing them to fall on to slow-moving conveyors. They fall on top of one another, and if the conveyor speed is carefully adjusted they will stack themselves with just the right amount of overlap to enable a pile to be quickly gathered by the operatives and placed on trucks for transport to the printing and box forming machines.

In order that the piles at the delivery tables will form in a uniform manner, the speed of these tables must follow the main board speed. But the required relative speed between delivery table and board depends upon the size of sheet being cut, so that a wide range of speeds is necessary on the delivery table. The board piece-length may vary over a range of 12 : 1 while the main machine speed can vary by 8 : 1, thus giving an overall speed range of 96 : 1 at the delivery table.

A speed range of this magnitude has been achieved with accurate control in a very simple manner by using individual Ward-Leonard control for the delivery-table motors. The generator fields are supplied from an auxiliary generator coupled to the double-facer motor, and through an adjusting potentiometer which enables the speed ratio to be set. The generator excitation thus follows the main drive speed in the correct ratio. A small magnetic amplifier compensates for machine load regulation, and a further fixed field on the generator is connected to overcome residual magnetism, which would otherwise make control at creep speeds impossible.

Conclusion

Ward-Leonard control with matched-regulation motors has provided a simple yet readily controllable drive for the machine, isolated from supply voltage disturbances. Where special control features are necessary magnetic amplifiers are used in preference to electronic units, as their long life and trouble-free running promote maximum production of packaging board from the installation.

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